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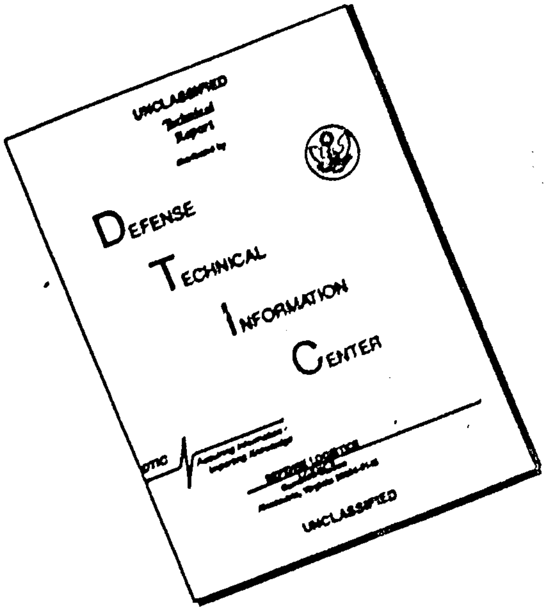

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A FORMAL SEMANTICS FOR COMPUTER ORIENTED LANGUAGES

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A FORMAL SEMANTICS FOR COMPUTER-ORIENTED LANGUAGES

by

Jerome A. Feldman

Submitted to the Carnegie Institute of Technology
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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PREFACE

In this thesis several aspects of the formalization of computer-oriented languages are considered. The emphasis has been placed on the practical results made possible by a formalization of the semantics of such languages. The most important of these results is the compiler-compiler which has been implemented using the formal systems described here as a base.

The author is deeply indebted to Professor Alan Perlis for his guidance in this work. He would also like to acknowledge the contributions made by the students of his undergraduate advanced programming course. Also of great value was the assistance of many members of the staff of the Carnegie Tech Computation Center, especially that provided by Messrs. D. Blocher and R. MacEwan and by Miss Nancy Lintelman.

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ABSTRACT

This dissertation presents a number of results attained in a study of the formalization of certain properties of computer - oriented languages. The most important result is a computer program which is capable of translating into machine language, any of a large class of source languages. Included in this class are all the usual high level problem-oriented languages.

The presentation of the results in the thesis is based on the structure of this program, called the compiler-compiler. Although there are several sections devoted to theoretical questions, these are set off from the main development. This organization was chosen so that the thesis could also serve as a user's guide to the compiler-compiler as a computer language.

A more detailed introduction to the paper is given ~~in Chapter I~~, where we also consider some of the philosophical questions raised by formalizing semantics. Chapter II contains a discussion of a formal syntax language used in the compiler-compiler. In this chapter we establish relationships between this formalization of syntax and others appearing in the literature.

Chapter III is a complete discussion of the Formal Semantic Language which is the main contribution of this thesis. In Chapter IV we show how the two formal systems were combined to form the basis

for a useful computer technique. The final chapter contains a discussion of the strengths and weaknesses of our system as well as several suggestions for future research.

The appendices ~~form an integral part of the thesis. The examples~~ contained there include a record of the development of a translator for one small language from a formal definition of the language to examples of resultant machine code.

I. INTRODUCTION

This thesis is a study of some theoretical and practical consequences of an attempt to formalize the semantics of computer-oriented languages. Among the languages in this class are the existing problem-oriented languages such as ALGOL 60 [31] and COMIT [43]. In addition, we include formalisms such as Markov Algorithms [30] which specify computational processes, but are not usually considered to be computer languages. Since the semantics definitions are to be processor-independent, we will usually not consider a particular machine order code as a computer-oriented language. Much more will be said about this situation in later chapters.

The emphasis in this paper will be placed on the practical results attainable from a formalized semantics. The most interesting application is in a computer program which will construct, for any computer-oriented language which has been appropriately described, a translator (compiler) for that language. This program would be a compiler-compiler for the machine on which it is implemented. Formalized semantics, combined with one of the known techniques for formalizing syntax, provides the facility for the complete formal description of computer languages. We have constructed a computer program, based on the formalisms described below, and have used it in the compilation of compilers for several well-known languages.

The entire formal scheme depends on a particular definition of the distinction between syntax and semantics. The definitions we have chosen differ from those used by most mathematical logicians, but do correspond to the intuitive notions of syntax and semantics.

We define an *alphabet*, $\mathcal{A}$, to be a finite set of symbols such that any string of symbols in $\mathcal{A}$ can be uniquely decomposed into its component symbols. For any such alphabet, $\mathcal{A}$, there is an infinite set, $\mathcal{U}$, of finite strings of symbols from $\mathcal{A}$. Any subset, $\mathcal{L}$, of $\mathcal{U}$ can be considered an *uninterpreted language* over the alphabet $\mathcal{A}$. A specification of a process which will select the subset $\mathcal{L}$ of $\mathcal{U}$ is called a *formal syntax* of the uninterpreted language $\mathcal{L}$. The process mentioned above need not be effective [10], but in this paper we will consider only languages with effective tests. The language in which the test is specified is called the *syntactic meta-language* used to specify $\mathcal{L}$. The selection process (syntax) of $\mathcal{L}$ may be either an algorithm for generating all the strings in $\mathcal{L}$ or an algorithm for deciding of a string in $\mathcal{U}$ whether or not it is in $\mathcal{L}$.

Any other well-defined operation on strings in $\mathcal{U}$ will be considered semantical. An uninterpreted language together with at least one semantic processor will be called an *interpreted language*. Although there are many interesting problems connected with uninterpreted languages, we will deal only with interpreted languages in this thesis, referring to them simply as *languages*. A formal system used to describe a semantic processor on some language, $\mathcal{L}$, is called a *semantic meta-language* of $\mathcal{L}$. The fact that it is possible to define uninteresting semantic operators will not concern us here.

In our formulation, the syntax of a formal language includes only a specification of which strings are permissible in that language. This is what logicians have called syntax in the narrow sense [9, p.58]. There are good reasons why logicians have chosen not to use our definition of syntax and why we have done so. As Church [9] points out, there is a sense in which the difference is not essential. In mathematical logic, it is usual to refer to any completely formalized operation within a system as syntactical. A simple example may help point out the difference in the two notions of syntax.

In any formulation of the propositional calculus (quantifier-free logic) there are two well-known algorithms for selecting strings from the set of all strings over the alphabet. One algorithm specifies which strings are well-formed according to the formation rules. A second algorithm describes a method for choosing those strings which are theorems. Both of these operations are considered syntactical in mathematical logic.

Using our definitions, one comes up with the following results. The operation which chooses the well-formed strings is once again purely syntactic. However, the nature of the theorem selection algorithm depends on what one considers to be the language, $\mathcal{L}$. If $\mathcal{L}$ is the set of well-formed formulas, then the theorem selector is a semantic operator. If we choose to consider the set of theorems in the predicate calculus as the language, $\mathcal{L}$, then the theorem selector is a formal syntax of that language.

A good discussion of why the wider definition of syntax is useful in logic may be found in Church [9, pp. 47-68]. The principle motivation behind our definitions is their close correspondence with the operation of compilers operating on digital computers. As we will show, the specification of the formal syntax and formal semantics of a computer-oriented languages contains all the information needed in a translator for that language.

In Chapter II we will discuss two types of syntactic meta-languages, with the emphasis on a particular recognizer-oriented language which has proved useful in building translators. Section II-A contains a description of this language as a programming language. In Section II-B we consider the formal properties of this syntactic meta-language in comparison with some well-known formal systems.

Chapter III contains a complete description of the semantic meta-language, FSL (Formal Semantic Language), which is the principle contribution of this thesis. The discussion treats FSL as a programming language and contains frequent references to the semantic description of a small language given in Appendix C. In Chapter IV we describe a computer program which builds, from a formal description of a language, a translator for that language. Although this program is highly machine dependent, we require the formal descriptions themselves to be independent of the machine on which the translator is run. In setting up such a scheme we have followed the semiotic of C. S. Pierce, introduced into programming by Gorn [21].

The semiotic concept of language is that it consists of three parts: syntax, semantics, and pragmatics. Syntax is concerned with the selection of those strings which are members of the language. Semantics consists of the meanings of a construct in the language independent of the interpreter involved. Those aspects of language introduced by the consideration of what is interpreting the language are called pragmatic. The interesting point is that we have been able to devise a useful trichotomy between these three aspects of computer-oriented languages.

As we have mentioned, the syntax and semantics of computer languages are to be described in machine-independent formal systems. Machine dependence (pragmatics) occurs in the programs which utilize the formal descriptions. The following block diagram should help illustrate how formal syntax and semantics can be used in a compiler-compiler.

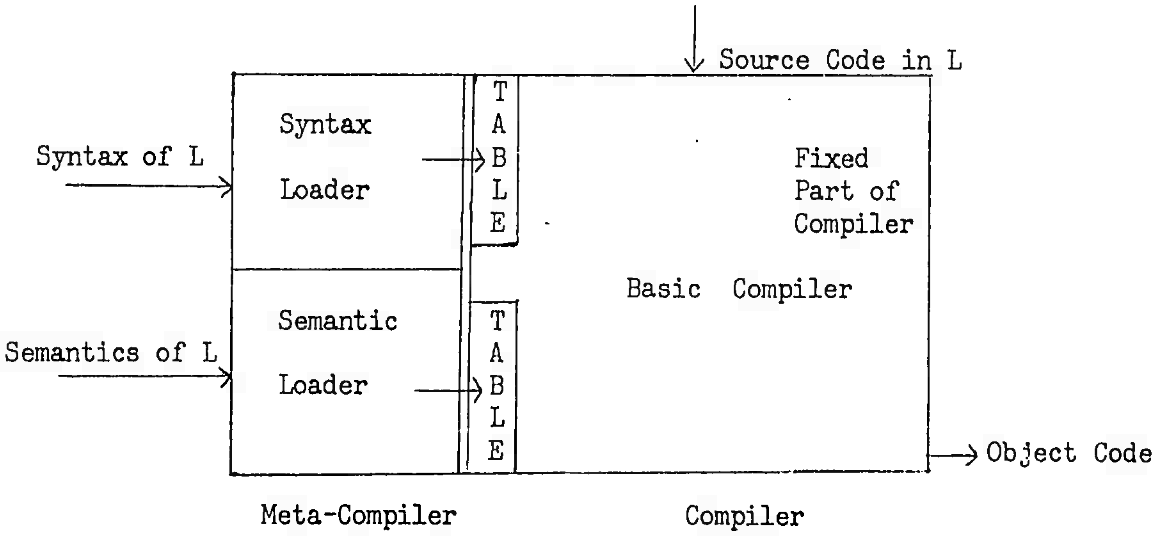

Figure 1.

When a translator for some language, L, is required, the following steps are taken. First the formal syntax of L, written in the syntax meta-language, is fed into the Syntax Loader. This program builds tables which will control the recognition and parsing of programs in the language L. Then the semantics of L, written in the Formal Semantic Language, is fed to the Semantic Loader. This program builds another table which in turn contains a description of the semantics of L.

The Basic Compiler is a table driven translator based on a recognizer using a single pushdown stack. Each element in this stack consists of two machine words -- one for a syntactic construct and one holding the semantics of the construct. The syntax tables determine how the compiler will parse a source language program. When a construct is recognized, the semantic tables are used to determine what actions are to be taken.

The entire system is based on the formalization of syntax and semantics, but not on the particular representations chosen. The remainder of this thesis will be largely devoted to a discussion of the two meta-languages used in the compiler-compiler at Carnegie Institute of Technology. The system has been running since early in 1964 and translators for such languages as ALGOL, FORTRAN, LISP and MARKOV ALGORITHMS have been written.

Chapter II of this thesis discusses the syntax meta-language used in our system. This language, Production Language, is similar to systems used for different purposes by Floyd [15], Evans [13] and Graham [22].

The most interesting feature of these systems is the absence of the explicitly recursive processes which are found in most syntax directed compilers.

The Formal Semantic Language (FSL) is described in Chapter III. The discussion there is basically a user's guide to the FSL system. Part of the FSL description deals with the semantic loader of Figure 1. Each of the three basic parts of Figure 1; syntax loader, semantic loader, and basic compiler, is a complex computer program. In Chapter IV we describe how these were combined to form a compiler-compiler.

In Chapter V we review and criticize the first four chapters. Among the topics discussed are the strengths and weaknesses of our system, the quality of translators produced and opportunities for future research.

The appendices form an important part of the paper. In Appendices A-C we describe a subset of ALGOL 60 called the "small language". Appendix A consists of the Backus Normal Form syntax of the small language. Its syntax in Production Language is Appendix B and Appendix C contains its formal semantics written in FSL. Throughout Chapters II and III there are references to examples taken from these appendices. Appendices B and C were used just as they appear to build a compiler for the small language.

Appendices D and E contain a formal syntactic definition of the Formal Semantic Language itself. The Backus Normal Form syntax is

Appendix D and the Production Language syntax is Appendix E. The question of writing the FSL semantics in FSL is discussed in the section of Chapter V which deals with weaknesses of the system.

Appendix F contains several examples of small language programs and their machine language equivalents. Thus Appendices A, B, C, and F enable one to follow the operation of the compiler-compiler from abstract syntax to machine code for the small language.

II. SYNTAX

A. The Production Language

For most computer scientists, formal syntax is synonymous with Backus Normal Form or BNF. The use of BNF to represent the formal syntax of ALGOL 60 [31] had a marked effect on the field. Its simple and precise specification of ALGOL syntax was a great improvement over the unwieldy English descriptions associated with previous programming languages. Besides improving human communication, the use of formal syntax has led to new formal developments in the theory and practice of programming.

Theoreticians were able to show that BNF grammars were capable of generating the same class of languages as those generated by several other formalisms. From the theory of natural languages came the Context Free Grammars of Chomsky [6] and the Simple Phase Structure Grammars of Bar Hillel [1], both equivalent to BNF. A mathematician, Ginsburg showed that BNF was equivalent to a formalism he called Definable Sets [20]. In addition, many results on the formal properties of such systems were attained.

The most interesting practical development was the syntax-directed compiler. If the syntax of programming languages can be represented formally, it should be possible to construct a language-independent syntax processor for a translator. As early as 1960, Irons [25] was able to write a translator whose syntax phase was independent of the source language being translated. This work and that of other early contributors such as Brooker and Morris [2] led to speculation that the entire translation process can be automated. This dissertation can be viewed as an effort in this direction.

With this weight of accomplishment behind BNF one might well question the usefulness of developing other syntax languages. Unfortunately, for several reasons BNF is inadequate as a universal syntax meta-language. We will present the theoretical weakness first and then discuss some practical difficulties and how they may be overcome.

As Floyd [18] has shown, Backus Normal Form is not capable of representing the language ALGOL 60 as defined by the English description in the report [31]. That is, not only is the BNF syntax in the ALGOL report inadequate to represent that language, but there is no BNF grammar that can do so. The concepts not expressible in BNF include relations imposed by the data types of declared variables and the number of parameters of subroutines. Since at least one of these constructs occurs in almost all programming languages, BNF is in some sense too weak to represent programming languages.

To make matters worse, there is a sense in which BNF grammars are too powerful. The languages generated by BNF grammars are sufficiently complex to have recursive undecidability play a significant role.

A problem in artificial language theory is undecidable if there is no single algorithm which will produce a solution in a finite time for any language in the class [10]. Bar Hillel [1] has shown that the following problems are undecidable for BNF grammars:

1) Do two grammars generate the same language?
2) Is the language generated by one grammar contained in the language generated by a second grammar?
3) Does a BNF grammar generate all (or all but a finite number) of the possible strings over its alphabet?

In addition, it is undecidable whether a single BNF grammar is ambiguous, i.e., if it generates the same sentence in more than one way [44]. These are questions one would like to be able to answer about programming languages and the results above indicate that, in general, this cannot be done for languages with BNF grammars.

The practical limitations on BNF grammars stem from their inherently recursive nature. The elegance of the recursive notation indicates implied processing, which on computers means slow processing. Although there are no proofs of such things, it is generally agreed (cf. [5], [22], [42]) that recursive recognizers are slower processors than the type described below. Intuitively, the speed difference arises from the housekeeping details incurred in recursive processing. There are many applications where greater human convenience compensates for this difference, but translator design does not seem to be one of these. Furthermore, error detection and recovery is more difficult in recursive recognizers [5]. A survey of the relation of formal syntax to programming may be found in an article by Floyd [17].

It was also Floyd who introduced an alternative notational technique, that of productions, into language analysis [16]. Like BNF, this production notation was originally devised to improve communication between people. It was so useful in representing symbol manipulation algorithms that it was natural to make a programming language from it. When an effort to implement ALGOL 60 was undertaken at Carnegie Tech, this notation was chosen for the coding of the syntax phase of the translator [13].

A good deal is now known about the theoretical and practical aspects of Production Language and other recognizer-oriented grammars. The theory [15] and practice [22] of bounded context grammars has received the greatest attention. Our Production Language system differs from those described elsewhere and thus will be presented in some detail below. The remainder of this section deals with the use of our system while its formal properties are discussed in Section II-B.

The Production Language, PL, is based on the model of a recognizer with a single pushdown stack. The syntax of a source language, when written in PL, will specify the behavior of the recognizer as it scans an input text in that source language. As a character is scanned it is brought into the stack of the recognizer. The symbol configuration at the top of this stack is compared with the specification of the source language being translated. When the characters in the stack match one of the specified configurations for the source language, certain actions are performed on the stack. If a match is not attained the stack is compared with the next PL statement. This process is repeated until a match is found or until the stack is discovered to be in an error state. The functioning of the recognizer will be discussed in connection with the example at the end of this section.

The format of a statement (production) in PL is given below.

Label L5 L4 L3 L2 L1 $\big| \longrightarrow$ R3 R2 R1 $\big|$ Action Next

In this format the first vertical bar from the left represents the top of the stack in the recognizer. The symbols L5...L1 in a given production will be characters which might be encountered in translating the source language. The symbol in position L1 is at the top of the stack. Only the top n characters $(1 \leq n \leq 5)$ need be present, the others being blank. If only three symbols are specified in some production, it will be compared with the three top positions of the stack during translation. The symbols L5...L1 constitute the "specified configuration" mentioned in the preceding paragraph. Any of L5---L1 may be the character 'σ' which represents any symbol and is always matched.

A match occurs when the actual characters in the stack during translation are the same as L5...L1 in the production being compared. At this time the remainder of the information in that production is used. The '→' following the bar specifies that the stack is to be changed. The symbols R3...R1 specify the symbols which must occupy the top of the stack after the change. If no '→' occurs then the stack will not be changed and R3...R1 must be blank. Thus L5...L1 refer to the top of the stack before and R3...R1 to the top of the stack after a production is executed which changes the stack.

An example of a production containing a '→' is found on line 11 of the fragment example at the end of this section. If this production is matched the characters on top of the stack will be

T * P σ

The execution of line 11 will leave the top of stack in the configuration

T σ

Such a production would be used in a language such as ALGOL to recognize a multiplication.

In the 'action' field of the production on line 11 there occurs 'EXEC 2'. All actions are performed after adjusting the stack as described above. The execution of EXEC 2 initiates the call of a semantic routine. In this case the semantic routine would cause the multiplication of the fourth and second elements in the stack. The value of the result would then be put in the second position in the stack and translation continued.

The semantic routines themselves are written in a special purpose language discussed in Section III.

The last part of the production in line 11 is the symbol 'T2' in the next field. This means that the next production to be compared with the stack is the one labeled 'T2'. (It is on line 13.)

The production on line 13 is an example of a production in which the stack is not changed. If this line is matched the symbol at the top of the stack is '*' denoting multiplication. At this point the translator requires another operand before the multiplication can be performed. Since no action can be taken, the production on line 13 does not change the stack and its action field is blank. In the label field of this production is '*P1'. The asterisk is this position is a special symbol of the Production Language and specifies that a new character is to be brought into the stack before transferring to the production labeled P1. The asterisk is equivalent to the command "SCAN" which may occur in the action field of a production. These are the only ways that a new character can be introduced into the stack.

Among the other commands which can appear in the action field of a production are EXEC, ERROR, and HALT. The action EXEC is the main link between syntax and semantics in our system and will be discussed in detail below. The action ERROR causes its parameter to be used in printing an error message for the program being translated. An execution of

HALT causes translation to end and, if there have been no errors, the running of the compiled code.

There is one feature of Production Language which does not appear in the syntax of the language fragment. It is possible to specify classes of symbols and use the class name in a production. This technique allows the user to replace many similar productions with one production. In Appendix B the class <TP> consists of the reserved words REAL, BOOLEAN, and LABEL. In the productions under D3, the class name <TP> is used in processing declarations in the small language, each production using <TP> replacing three productions.

The remainder of this section will be a discussion of the example on page 20. The language fragment description in the example is a subset of the syntax of arithmetic expressions in a language such as ALGOL 60.

The mnemonic significance of the letters in the example is related to the ALGOL syntax and is given in the following table

Letter	May be Read
I	Identifier
P	Primary
T	Term
E	Expression

The parentheses, asterisk and minus sign have their usual meanings. There are no productions to recognize identifiers because this is done in a pre-scan phase. We will assume that the production syntax of the rest of the language is compatible with the fragment.

The productions under the label P1 (lines 7-10) are used when a primary is expected. Line 7 is matched if the primary is preceded by a unary minus sign. In this case the minus is left in the stack where it will be processed by line 15. Similarly, the parenthesis in line 8 is left in the stack to be processed by line 18 when its mate is scanned.

In line 9 an identifier is recognized and changed to a primary. Then EXEC 1 will initiate a call of a semantic routine which will see if the identifier is properly defined and, if so, will assign the value associated with that identifier to the primary.

Any other character appearing in the stack at this point is a syntactic error. This is expressed in line 10 where the action field contains an error message.

Line 11 recognizes a multiplication and has been discussed earlier. Line 12 (also 16) only changes the name of the symbol in the stack. This device is used to enable the productions to realize the rule of arithmetic that requires multiplication to bind more tightly than subtraction. The production in line 13 embodies this implementation. If a term is followed by an '*', there is a multiplication which must be performed before that term is used in any subtraction. For this reason line 13 brings a new symbol into the stack and causes a transfer to P1 to pick up the other operand for that multiplication.

The productions under E1 (lines 14-16) recognize subtractions and form the final expressions. Those under E2 (line 17-20) process an expression once it is recognized. If the expression is followed by a minus, it is part of a larger expression so line 17 returns control to P1 to process the remainder. The production on line 18 embodies the rule that all operations within parentheses must be executed before the parenthesized expression acts as an operand. If the fragment were imbedded in a full language (e.g., Appendix B) other uses of arithmetic expressions would be checked for under E2. In the fragment, expressions are used in just the two ways described above so that any other character in the stack leads to an error condition.

The label Q1 is assumed to lead to an error recovery routine. For an example of a sophisticated error recovery scheme using production language see reference [13].

The production syntax for a complete programming language is included as Appendix B of this paper. The Backus Normal Form syntax of the same language is Appendix A. A word is in order regarding the equivalence of a BNF and a PL grammar. Nowhere in this paper is there an attempt to present a formal proof of the equivalence of two such grammars. The writing of productions is in essence a constructive programming task and discrepancies should be treated as 'bugs' in a program. To the best of our knowledge the examples are all debugged.

The task of writing productions is not a difficult one. The productions for the small language (Appendix B) were assigned, with good results, as a homework problem in an undergraduate programming course. In fact, one of the students wrote a program in IPL-V which converts a BNF specification of a language into productions for a large class of languages. This work will be reported in a forthcoming paper.

BNF Syntax of a Language Fragment

< I > :: = <letter> | < I > <letter> | < I > <digit>

< P > :: = < I > | (< E >)

< T > :: = < P > | < T > * < P >

< E > :: = < T > | - < T > | < E > - < T >

Production Syntax for the Same Fragment

LABEL				LEFT			RIGHT	ACTION	NEXT
P1				-|			|		*P1
				(|			|		*P1
				I|	→		P|	EXEC 1	*T1
				∅|			|	ERROR 1	Q1
T1	T	*	P	∅|	→	T	∅|	EXEC 2	T2
			P	∅|	→	T	∅|		T2
T2			T	*|			|		*P1
E1	E	-	T	∅|	→	E	∅|	EXEC 3	E2
		-	T	∅|	→	E	∅|	EXEC 4	E2
			T	∅|	→	E	∅|		E2
E2			E	-|			|		*P1
		(	E	)|	→		P|	EXEC 5	*T1
				∅|			|	ERROR 2	Q2

Figure 2.

B. Formal Properties

The Production Language used to describe the syntax of various source languages is a formal grammar. There has been much research done on the mathematical properties of such formal grammars and in this section we will discuss the relationship between Production Language and some well-known grammars.

Most of the formal grammars whose properties have been studied are generator-oriented. A generator-oriented grammar for a language, L, is a set of rules for generating the sentences of L. The generation rules are applied recursively to strings of characters, starting with a fixed initial symbol. Various schemes have been devised to classify these grammars according to the complexity of the languages they specify. We will follow the terminology of Chomsky [6] in describing a hierarchy of languages types.

In his definitive paper, Chomsky describes four types of grammar and shows that each is capable of generating more complex languages than its successor in the hierarchy. The most general grammar he considers in Type 0, which allows as a grammar essentially any finite set of rules for transforming character strings. The other types are obtained by placing various restrictions on the permissible rules.

In TYPE 1 grammars, the restriction is that each application of a generation rule does not decrease the length of the sentence being generated. The TYPE 2 grammars may be characterized by the restriction that each rule specifies the replacement of a single character, independent of its context. The weakest grammars, TYPE 3, allow only those replacements which effect a transformation on only one end of the sentence being generated. Chomsky gives a precise definition of those four types, establishes the hierarchy, and then relates these formalisms to some well-known mathematical constructs.

The class of TYPE 0 grammars is shown to be equivalent to the class of all Turing machines, i.e., for any computations performable on a Turing machine there is a TYPE 0 grammar which will perform equivalent string transformations. Turing machines, and thus TYPE 0 grammars, are capable of executing any computable function. (cf. Davis [10])

TYPE 1 grammars are called context-sensitive because the replacement rules may depend on the context of the character being replaced. These have been used less than the other types, but do have the interesting property that they are decidable, i.e., for any TYPE 1 language there exists an algorithm for determining if a given string in its alphabet is a sentence of that language.

The TYPE 2 or context-free languages have received the widest attention in the literature. These are equivalent to the formalisms: Simple Phrase Structure Grammars [1], Definable Sets [20], and to Backus Normal Form [32]. It is this last equivalence which has made TYPE 2 grammars interesting to workers in programming languages. Despite its theoretical inadequacies, Backus Normal Form has established itself as a canonical form for the description of syntax of artificial languages. In this section, we will discuss the formal properties of the Production Language as compared with those of Backus Normal Form.

In this discussion we will make use of results by Chomsky [7] and Evey [14]. In independent efforts, they attempted to construct automata which would be equivalent to Backus Normal Form. We will follow Chomsky in presenting the definition of a Push Down Store Automaton. This automaton is recognizer-oriented and will, in fact, be shown equivalent to the Production Language. A pushdown store automaton, M, consists of a finite state control unit and two unbounded tapes, an input and a storage tape. The control unit can read symbols of the input alphabet A_I from the input tape and the symbols of the output alphabet $A_0 \supset A_I$ from the storage tape. It can also write the symbols of A_0 on the storage tape. If M is in the state S_i scanning the symbols a on the input tape and b on the storage tape, we say that is in the situation (a, S_i, b). There is an element a_0 which cannot appear on the input tape nor be written on the storage tape. At the beginning of a computation, M is in the state S_0, with the storage tape containing a_0 in every square and the input tape containing a string $b_1 \ldots b_n$ in the first n squares. After b_n, the input tape has a special symbol # in every square. A computation ends when the M returns to the state S_0. If at this time M is in the situation (a_0, S_0, #) we say it accepts (recognizes) the string $b_1 \dots b_n$.

A computation of M is controlled by a set of rules of the form

$$(1) \qquad (a, S_i, b) \longrightarrow (S_j, X, K)$$

where $a \in A_I$, $b \in A_O$; X is a string in A_O and S_i, S_j are states of the control unit. If $X = \mathcal{a}_0$ then k = 0 or -1, if $X \neq \mathcal{a}_0$ then k = length of X. We can assume, without loss of generality that $b = \mathcal{a}_0$ only if $S_i = S_0$ and $K \leq 0$. Then the instruction (1) applies when M is in the situation (a, S_i, b) and has the following effect: The control unit switches to state S_j, one symbol is removed from the end of the input tape and the storage tape is moved k squares left, with X being filled into these squares. After the instruction, M is in the state (c, S_j, d) where c is the symbol to the right of a on the input tape and d is the rightmost symbol of X. If k is -1 the storage tape is shifted one to the right, effectively erasing the symbol which was rightmost on this stack. In the special case that $a = \mathcal{a}_0$ the contents of the input tape are ignored and that tape does not move.

We will now show that each pushdown store automaton is equivalent to a program in the Production Language of Section II. For this purpose we first rename some of Chomsky's constructs. The storage tape will be called the stack. The input tape is just a device for holding the input text and will not be mentioned explicitly.

For each state S_i in M we set up a label S_i in PL and then associate all situations in state S_i with productions occurring under the label S_i. Then we make a transformation on the format of the instructions of M. The situation on the left of an M-instruction looks at the top of the stack and the next input symbol. Since all input symbols are contained in the output alphabet, it is equivalent to look at the top two characters in the stack. Then we could write an M-rule as

$$(2) \qquad (ba, S_i) \longrightarrow (S_j, X, K)$$

Now notice that the parameter k is redundant except when X is null and in this case it is either 0 or -1. In the latter case, the corresponding production would either leave the stack alone or execute a production which removes the top element of the stack. Then eliminating k and remembering that labels in productions correspond to states in M, we get the rule

$$(3) \qquad S_i : \quad b \;\; a \rightarrow X \qquad *S_j$$

which is almost in production language form. The remaining difference is that X may have more than three characters in M and that productions may look at as many as five characters on the left. In either case, the longer symbol string can be replaced by a succession of shorter replacements by adding extra symbols to Λ_0 in the usual manner.

To complete the correlation between productions and pushdown store automata we need two other facts. In productions one can have a rule using 'σ' which is always recognized - the automaton M allows the symbol a_0 to appear in a rule specifying that any character will match that rule. Further, in this case the input string does not move, corresponding to a production rule without '*' in the label field.

The preceding paragraphs outline a procedure for converting a pushdown store automaton into a production language program. Since all of the steps are reversible, the two concepts are equivalent in the sense that they will recognize the same class of languages. This is of interest here because of some known results on the formal properties of pushdown store automata. We will present Chomsky's main theorem, which is apparently a complete characterization of Production Language, and then show why this is not the case.

Theorem (Chomsky) A language L is accepted by a pushdown store automaton if and only if it is a TYPE 2 language.

In the proof of this theorem Chomsky first reduces the replacement rules of any TYPE 2 grammar to a simple canonical form. Then, through an intermediate step, he is able to invert each replacement rule and produce a set of recognition rules which specify the equivalent automaton. This would, indeed, solve the problem if it were not for the following difficulty.

In the inversion process it may happen that many automaton instructions with the same left side are formed. There is no specification of which rule is to be executed first in such a case. What the theorem states is that, in each case, there is a choice which will lead to the recognition of a particular TYPE 2 sentence. Chomsky describes this as the non-deterministic operation of an automaton and does not concern himself with the implementation of such a device.

For us, however, implementation is a key issue. To implement such a scheme would require another storage tape to hold temporary information while each alternative was tried. The maximum amount of storage is a function of the length of the input string and the complexity of the automaton. Whether such an automaton could be weaker than a Turing machine is an interesting question which we do not pursue here. These non-deterministic automata are related to the multiple-path syntax analyzers used by Kuno and Oettinger [27] on natural languages. For artificial languages where syntax is more precise, we consider non-deterministic automata too inefficient to be of interest.

A question arises as to whether there are any TYPE 2 languages which actually require a non-deterministic recognizer. One well-known example of such a language is the odd palindromes over the alphabet '0' and '1'. The syntax of this language in Backus Normal Form is:

$$W ::= 0 \mid 1 \mid 0W0 \mid 1W1$$

where W names the set of well-formed sentences. A pushdown store automaton for this language would require non-deterministic control.

The results of the preceding paragraphs may be summarized as follows. There is a sense in which the Production Language is equivalent to Backus Normal Form. This formal equivalence is unsatisfactory because we are not willing to use productions in the inefficient manner specified by the equivalence theorem. Further, there are simple languages which are expressible in Backus Normal Form and which cannot be efficiently recognized by productions.

There is, however, a construct in Production Language which we have not yet mentioned. This device wasn't used in any of the example in Section II-A and apparently would not add to the formal power of the language. The extra construct is simply the ability to call any labeled set of productions as a subroutine. This is done by placing a statement of the form

SUBR L

in the 'action' field of a production. The parameter 'L' is the label of the set of productions being called. The action RETU is executed at the end of a subroutine. These subroutine calls are allowed to be recursive; a subroutine can contain a call of itself.

It is the last feature which indirectly introduces the extra power into Production Language. Since a subroutine may be called many times before it finishes once, a stack of return addresses (marks) must be kept. As is well known, one stack can keep the marks for all the subroutines. For simplicity we will assume that all implementations of Production Language are of this form. The crucial point is that there may be any number of nested subroutine calls so this stack of marks must be unbounded.

Now, as Evey [14] has shown, an automaton with two unbounded stacks is equivalent to Turing machine. This is intuitively clear if we picture the two stacks as the two ends of a tape which is unbounded in either direction. Then the Turing machine operation of moving the tape is paralleled by switching a character from one stack to the other. There is one difficulty with this picture in the case of the Production Language. Here one of the stacks contains symbols of A_0 and the other stack only marks for subroutines. This difficulty is circumscribed by what can only be called a programming device.

We add to a Production Language program two sets of productions for each symbol of A_0. The first set will have the effect of removing the top character from the stack and leaving an address in the mark stack. Thus when a character is to be moved to the second stack a unique address is put there in its stead. Now, when a symbol is to be put back in the main stack, the action RETU is executed. This causes a transfer to the 'next' field of the production which called the subroutine. The label in the 'next' field will lead to a production which puts the appropriate symbol back in the main stack. Thus we have established a 1:1 correspondence between symbols in the main stack and addresses in the mark stack. This correspondence and the two transfer functions allow us to treat the two stacks jointly as the tape of a Turing Machine.

In this section we have attempted to define the formal properties of the Production Language. By varying slightly the side conditions on the use of productions we arrived at three very different characterizations of their power as an automaton. There are two important lessons to be learned from these examples. The first, and most important, concerns the relation of actual computer techniques and the formal structures used to model them. Since the formal model is precise and relatively tractable, there is a tendency to discuss the model as if it were the system itself. The examples of this section show that there may be several formal models, with quite different properties, of one programming construct.

The other point to be made is a practical one. We were able, through clever programming, to make Production Language equivalent to Turing machines. The problem is that one would rarely use productions in the manner required in the demonstration for translating a programming language. We have shown that the power is in the system, but have not shown how to use this power effectively. It would be interesting to see if there were some practical way to utilize the extended production language to develop efficient recognizers for more complex programming languages.

In the remainder of this paper, productions will only be used in the weakest of the three ways described here. Although it is theoretically possible to do complete syntax checking with productions, we have found it more efficient to defer some of the checking to the semantic phase. An interesting side effect of this decision is that it is impossible to specify an ambiguous language using productions in the weak sense. We will consider some of the practical problems connected with production grammars in Chapters IV and V.

III. FORMAL SEMANTICS

A. Introduction

This section of the paper is devoted to a detailed discussion of the Formal Semantic Language, FSL. This language embodies an attempt to state in fixed terms the meaning of a statement in any of a large class of programming languages.

The formalization of the semantics of some language, L, will involve representing the meanings of statements in L in terms of an appropriate meta-language. If L is a computer language, the semantics of L must involve a description of its translator. Throughout this paper we will use the neutral word 'translator' to mean either a compiler or an interpreter. The distinction between these latter concepts is not clear cut, since many compilers use run-time routines and many interpreters incorporate a preprocessing phase. We will use terms like 'highly interpretive translator' to indicate that a translator is more like one or the other of these extremes.

The meanings of statements in the meta-language are assumed to be known (primitive). An example of a semantic meta-language would be the order code of a computer. An order code or assembly language can certainly describe any translation possible on its machine and, in fact, these have been the only kinds of semantic meta-languages in general use to date.

Unfortunately, these lack several properties which one would like to see in a semantic meta-language.

A semantic meta-language should allow the description of source languages to be as easy as possible. It should be readable so that other people can understand the meaning of the source language being defined. It should enable a description of a language which is precise and complete enough to allow for automatic compilation. Finally, the meta-language description should be independent of any particular machine.

These criteria are easily recognizable as those relevant to the specification of a problem-oriented computer language. The problem involved is the representation of the meanings of statements in a computer language. The Formal Semantic Language presented here is an attempt to provide a complete programming system possessing these properties.

The semantic meta-language, FSL, was designed to have just those constructs which are useful in describing translators. These were chosen with no thought of implementation and no particular computer in mind. After the system was complete, users began to attempt the writing of semantics for some common programming languages and its implementation was begun. The interaction of these three forces, preconceived formalism, hardware implementation, and human users, forged the system into its final form. An FSL system is running on the Control Data G-21 at Carnegie Tech, and translators for several languages including FORTRAN, ALGOL, and LISP have been written.

The basic unit in an FSL program is the labeled statement or sentence. These labels are integers and form the main link between the productions described in Section II and the semantic routines discussed here. As we recall, a production may include an action of the form

EXEC n

where n is an integer. The semantic routine labeled 'n' will be executed each time that production is matched.

Whenever possible, the discussion of a construct in FSL will be accompanied by an example. The examples will be drawn from the translator for a subset of ALGOL 60 which we call the "small language". The BNF syntax of the small language is Appendix A of this paper. The productions for the small language constitute Appendix B while the formal semantics is Appendix C. Appendices B and C comprise a complete description of the small language and have been used in the construction of a compiler for that language.

In many ways, FSL is similar to other programming languages. Various concepts have been borrowed from different algebraic and list processing languages. As is the case in programming research, it is impossible to accurately credit one author as the originator of an idea. There is also a 'folklore' of unpublished techniques upon which we have drawn freely. But there are also many constructs in FSL which are peculiar to the translation problem and which have not appeared before. The introduction of each new construct was prompted by some problem in language design.

One of the most difficult concepts in translator writing is the distinction between actions done at translate time and those done at run time. Anyone who has mastered this difference has taken the basic step towards gaining an understanding of computer languages. This difference between run time and compile time actions is a crucial one in FSL and is always represented explicitly. The means of doing this is the pair of code brackets 'CODE(' and ')'. Any statement enclosed in code brackets specifies an action to be taken at run time, while any statement not so enclosed describes action taken at translate time. As we will see, each FSL construct has two meanings, one when it appears inside code brackets and the other when it does not. In some cases, one of the meanings will not be defined.

Some of the other unique features of FSL are the tagging facilities. There are special statements for putting on or removing tags and a predicate used to test for the presence of a given tag. These are usually used in connection with various data types and are discussed in Section III-C.

There are also FSL constructs which effect the translation of forward references in a source language program. These constructs formalize some efficient techniques used by translator writers to handle forward references. They include floating addresses, discussed in Section III-D and chains, discussed in Section III-E. Also used in this connection is an 'assign' statement described in Section III-F.

In addition, FSL includes indirect addressing at both translate time and at run time. It also allows a more general replacement statement than is usually found in programming languages. These features are useful in computing addresses for use in compiling code and are discussed in Sections III-D and III-F.

Some of the more interesting features arise in connection with storage for the translator itself. Each FSL program describes a translator and thus must include a description of the storage the translator will use in building up code. The various storage types available in FSL are described below.

B. Storage Declarations

One of the major difficulties involved in the translation of computer languages arises because the meaning of a statement will, in general, depend on that of preceding and even of succeeding statements. For example, most programming languages allow the declaration of data types and the subsequent use of defined variables in various contexts. In this case the meaning of a statement depends on the data type declared for the variables involved in that statement.

There is at least one well known example of the use of succeeding information in programming languages. It is very common to have a jump or transfer to a label which is not yet defined. The meaning of such a statement is not available until the label is defined somewhere in the succeeding text.

For reasons such as these, one might expect some fairly sophisticated storage operations in a language which purports to formalize the translation process. In the Formal Semantic Language (FSL) there are five distinct types of storage available to the language designer. These are introduced as declarations in a FSL description of a language and become part of the translator for that language. All of these declarations must be at the beginning of the FSL program and no declaration may occur within code brackets. The declaration of translator storage is covered in this section while the operations available for declared storage will be treated in III-C.

The first and most complex data type in FSL is the TABLE. Conventional translators often have tables for variables, for labels, for subroutine names and for a variety of other constructs. These usually exist only at compile time but in highly interpretive translators, tables may be required at run time as well. In FSL a run time table is declared by a RTABL declaration while compile time tables are declared by a TABLE declaration. The syntax is:

```
< table dec > ::=  TABLE < table specifier >|
                   RTABL < table specifier >|
                   < table dec > ,  < table specifier >

< table specifier > ::=  < identifier > [ <integer>,<integer> ]
```

The <identifier> is the name of the table being declared. The first integer specifies the maximum length of the table and the second integer specifies the number of entries (width) of the table. In the next section we will discuss the operators for entering information into and retrieving it from these tables.

The small language described in Appendices A - C is a pure compiler and thus has no run-time tables. The one table, SYMB, declared in Appendix C would be the symbol table for the translator. It would hold the identifier (name) of a variable and its location, data type, and level for each variable declared in a particular source language program. SYMB, as declared, can hold four entries for each of a maximum of 800 symbols.

The description of all the other storage types makes use of the construct <identifier list> :

<identifier list> :: = <identifier> | <identifier list>,<identifier>

Thus each declarator operates on a list of variables, eliminating the use of redundant declarators.

In recent years the push-down stack has become an indispensable tool to translator writers. It is possible in FSL to declare stacks which will exist either at compile-time or at run-time. The syntax is:

<stack dec> :: = STACK <identifier list> |
RSTAK <identifier list>

There are no run-time stacks in the small language. The two stacks, STR and SYM, declared for the compiler will be used in connection with the block structure. At the beginning of each block, STR will have stored in it the value of the storage pointer and SYM the value of the symbol table pointer. At the end of a block these two pointers can be replaced, allowing the translator to reuse both storage and table space. These operations occur in semantic routines 2↓ and 29↓ .

Individual storage locations for use in the translator are declared to be of type CELL:

<Cell dec> :: = CELL <identifier list>

A cell may be used as a switch, a temporary or any other object requiring a single machine location at translate time.

It is often useful in translator writing to have certain marks of constant value. One may declare alphabetic constants in FSL as variables of type TITLE:

<title dec> :: = TITLE <identifier list>

The title words used in the small language are the three data types: REAL, BOOL, LABE. When an identifier is declared, the appropriate title word is entered into the symbol table. Then when an identifier occurs in a statement, a test is made to see if the identifier is of the proper type, i.e. if its TITLE word is one acceptable in this context. If it is not, an error message will be printed.

The fifth type of declaration in FSL is DATA:

<data dec> :: = DATA <identifier list>

The variables declared to be of type DATA specify bit configurations rather than entire computer words. A translator works primarily with addresses and in most computers an address is not as long as a word. The operators associated with DATA identifiers enable the translator writer to tag an address with certain bits and later test if the bits are present. The use of DATA variables will be discussed in detail in Section III-C.

The data variables used in the small language are LOGIC, INTEGER, SINGLE, DOUBLE. There are several instances of their use in the semantics of the small language (Appendix C).

The various declarations described above must occur together at the beginning of an FSL program. The syntax of the declaration part of a program is:

```
<declaration part> :: =  <declaration>|
                         <declaration part> ; <declaration>
<declaration> :: =  <table dec> | <stack dec> | <cell dec>
                    <title dec> | <data dec>
```

C. Storage Operations

We have already introduced several means of declaring storage for a translator. Each type of storage has associated with it a set of operators which enables the language designer to use the storage effectively.

Storage variables declared as type CELL or of type TITLE are single storage locations and require no special operators. Any such variable will be of type <operand> and as such will be discussed in Section III-D.

There are two basic operations on STACKS, PUSH and POP. Each has two parameters, the first being the name of a stack and the second specifying a location. An execution of PUSH causes the contents of specified locations to be appended to the top of the stack. The command POP will cause the top element of the stack to be stored in the specified location and to be removed from the top of the stack. The syntax of stack commands is:

```
<stack command> :: =  PUSH [ <identifier> , <arithmetic> ] |
                      POP  [ <identifier> , <arithmetic> ]
```

In addition, the name of any stack can be used as an <operand>. In this case the top element of the stack is treated as a variable which can be accessed or stored into. Thus there are commands for the destructive and non-destructive reading and writing of stacks.

In the small language semantics, stacks are used only in connection with block structure. Semantic routine 1↓ has two instances of the destructive store into a stack.

```
1↓  LEV ← 0;  STR ← STORLOC;  SYM ← LOC[SYMB]  ↓
```

Routine 2↓ demonstrates the non-destructive (pushdown) store into the same stacks. Two examples of destructive read out occurs in 29↓. There are no non-destructive reads in the small language.

```
 2↓  LEV ≠ 0 → PUSH[STR,STORLOC]; PUSH [SYM, LOC[SYMB]]$  ;
      TALLY[LEV] ↓
29↓  MINUS[LEV];  POP[STR,STORLOC]; POP[SYM,LOC[SYMB]] ↓
```

If a stack command occurs within code brackets the identifier must have been declared to be of type RSTAK. In this case the stack operation will be performed at run time. Since the small language requires no RSTAK variables, all stack commands in Appendix C are outside code brackets.

Both STACK and RSTAK are implemented using a pointer. That is, when a stack identifier is used in a PUSH command, the pointer for that stack increases by one. Similarly, a POP causes the pointer to be decreased by one, after the store is done. The pointer associated with any stack is also available to the FSL user. It is referred to as

LOC [<stack id>]

where the <stack id> is the name of the stack as declared with a STACK or RSTAK statement.

Since the run time stacks are not available at compile time, the use of RSTAK variables outside code brackets is forbidden. The general rules for compile time operands within code brackets will be discussed in Section III-D.

The variables declared to be of type DATA are used only with specific data operators. There is a special command, SET, for putting the tag associated with a data identifier into a machine word. The syntax of the set command is

SET [<arithmetic> , <data id>]

where the value of <arithmetic> is the location which is to be set. The effect of a SET is to unite the current contents of the location specified by the arithmetic expression with the bits corresponding to the <data id>. An example may be found in 4↓ of Appendix C which is executed when a real variable has been declared. The contents of TO are united with the bits for DOUBLE and the result put back in TO, which is then put in the symbol table, SYMB.

```
4↓    TO ← STORLOC; SET[TO,DOUBLE]; ENTER [SYMB;LEFT2,TO,REAL,LEV];
      STORLOC ← STORLOC+2 ↓
```

The FSL system itself can currently recognize and compile code for the four data types: LOGIC, INTEGER, SINGLE, and DOUBLE. Any variable that is set to have one of these types will be treated automatically. In addition, the language designer may choose to use other data names such as COMPLEX, ARRAY, or TREE. Any variable declared of type DATA will have a unique set of bits associated with it. One can, for example, design a language with complex arithmetic as a basic set of operations. Each complex variable could be set COMPLEX and recognized as such in a later arithmetic statement. The actual semantics of each complex operation would, however, have to be written in terms of the operations on SINGLE or DOUBLE variables which are part of the system.

To make effective use of DATA variables, one must have a way to test for the presence of bit patterns. This is provided in FSL by means of a binary predicate, TEST. This predicate is one instance of a <boolean primary>. The syntax is:

TEST [<arithmetic> , <data id>]

The value of the predicate is TRUE if the bit pattern corresponding to the <data id> is present in the location named by the <arithmetic>. The value is FALSE in any other case. The location named by <arithmetic> is not changed by the TEST.

In the small language described in the appendices, real variables are used in double precision form. Therefore in 4↓, when an identifier is declared to be real, its location is set to DOUBLE. It should be noted that none of the statements dealing with arithmetic operations (10↓ - 14↓) contains a TEST. This is because the small language contains only data types which the system treats directly. The addition of two variables set with the bits for DOUBLE will automatically be compiled by the system as a double precision operation.

A potential difficulty arises in connection with variables which have been tagged. If one were to attempt to do arithmetic at compile time on tagged addresses, the tags would affect the arithmetic operations in unpredictable ways. For this reason, there is a special operator, CLEAR, in FSL. The syntax is:

```
CLEAR [ <arithmetic> ]
```

The location specified by the <arithmetic> names the location to be cleared. The effect of a clear is to remove all the tag bits from a machine word. The DATA identifiers name only portions of a machine word and thus may not be used except as described above.

The most complicated data structure in FSL is the table. In Section III-B we described the manner in which tables are dec'ared in FSL. The one table in the small language translator was seen to have four entries for each variable used in a small language program. These entries are filled in by the operation ENTER. The syntax of the enter command is:

```
<enter> :: = ENTER [ <table id> ; <expression list> ]
<expression list> :: = <arithmetic>|<expression list>,<arithmetic>
```

The number of expressions in the list should equal the width declared for the table. The ENTER statement will form the expressions in the list, in order, as a row of the table name by the <table id>. If the table is already filled, no stores will be done and the cell SIGNAL will be set FALSE.

In the semantics of the small language (Appendix C) there are three examples of the use of ENTER. These occur in connection with the declaration of the three kinds of variables in routines 4↓ , 5↓, and 30↓. As each variable is declared, the small language translator alters its symbol table, SYMB. In each case an enter command is used to form a new row of the symbol table.

For example, in 4↓ a new row of the symbol table SYMB is formed as follows. The next available storage cell is picked up and SET to have the type title. The row of SYMB will consist of the name of the variable (in LEFT2), the tagged address, the title REAL and the current value of the cell LEV.

```
4↓   TO ← STORLOC; SET[TO,DOUBLE]; ENTER[SYMB;LEFT2,TO,REAL,LEV];
     STORLOC ← STORLOC+2  ↓
```

We now know how to declare tables and how to store into them. In order for tables to be useful, there should also be a convenient way of retrieving information. Since a table element will most often be used as a operand,the retrieval routine is of the syntactic type <operand>. This enables the FSL programmer to use table entries directly as operands. The syntax is:

```
<table operand> :: =  <table id> [<arithmetic> <commas> $ <commas>]
<commas>        :: =  , | <commas> , | <empty>
```

The selection of a table operand takes place in three distinct steps. First the value of the <arithmetic> is computed and saved. Then the table named by the <table id> is searched for an occurrence of this value as the first entry of a row. When a match is found the position of the $ is used to pick out the desired entry in the matched row.

An example should help clarify the use of table operands. Consider semantic routine 16↓, which is called when an arithmetic assignment statement has been scanned.

```
16↓   SYMB[LEFT4,,$,]=REAL→ COMT 2←SYMB[LEFT4,$,,];
      CODE(COMT 2←LEFT2) ; TEMPLOC←T3 : FAULT 3$  ↓
```

The fourth element in the stack at this point (LEFT4) is an identifier which names the location to be stored into. In 16↓ the identifier is looked up in the symbol table and the third entry in the matched row is selected as the operand. As we recall, this entry should be the data type of the variable. If the data type is not REAL, a semantic fault is detected.

If the identifier was declared correctly the assignment statement should be compiled. For this purpose the address which the variable will have at run time is needed. The next statement in 16↓ selects this address (the second entry in the row named by the identifier) and stores it into a cell named COMT 2. We will see later how this address is used in compiling the code for the store operation.

As we mentioned, the selection of a table operand takes place in three distinct steps. First the expression to be looked up is computed. Then the table is searched for a match and finally the correct entry in the matched row is selected. It is often the case that more than one entry from a specific row is needed in a single routine. In such cases, it should be possible to bypass the first two parts of the selection process for all but the first of these operands.

There is a special convention in FSL to enable the user to take advantage of this possibility. If the <arithmetic> in the specification of the table operation is '0' the last row selected is automatically used, bypassing the first two steps of the selection process. This is useful when successive references to the same row of one table are used within a semantic routine. Although this feature could have been used in many of the semantic routines in Appendix C (e.g. 8↓, 9↓, 16↓) it was omitted for the sake of clarity. The one example of its use is in 26↓. Each table declared in FSL is implemented using a pointer to the next available row. This pointer is also used by the retrieval routine as the starting points of its search. In addition, the pointer for each table is available to the user as an <operand> of the form

LOC [<table id>]

In the small language, the table pointer is used in connection with the block structure. At the beginning of each block, 2↓ will be called and it will cause the pointer for SYMB to be saved. Routine 29↓ , which is called at the end of each block, resets the pointer to its value on entering that block. This effects the elimination of all variables which were declared to be local to the block.

It is important to remember that all of the storage constructs described above are defined for the translator only. The language designer may choose to incorporate any of a number of different kinds of storage in his source language. The storage allocation for programs written in a particular source language is part of the semantic description of that language. We will discuss in Section III-G some special features of FSL which facilitate the solution of storage problems in a source language.

D. Operands and Primaries

The basic unit in FSL is the operand. We have already encountered several instances of operands in the discussion of storage in III-B and III-C. In this section we will introduce the other operands and discuss their use. The material below presupposes an understanding of the significance of code brackets as presented in III-A. The meaning and use of each operand will depend upon whether or not it is inside code brackets.

We will first present the syntax of <operand> and then discuss each instance in the definition.

```
<operand> ::= <storage operand> | <production operand> | COMT␣<identifier> |
                    RUNT␣<identifier> |  ⟨<arithmetic>⟩  ;
```

The storage operands have been discussed in some detail in III-C. Their syntax is:

<storage operand> :: = <table operand> | <cell id> | <stack id> | <title id>

The identifiers of type TITLE each name an alphabetic string extant at compile time and thus have no meaning within code brackets. Both table and stack operands involve address computations each time they are used. For this reason variables associated with RSTAK and RTABL can occur only within code brackets, specifying actions to be performed at run time. Similarly, STACK and TABLE operands must be computed at compile time and thus never appear within code brackets. This is in keeping with the convention, adhered to in FSL, of distinguishing explicitly between actions performed at run time and those done at compile time. Identifiers of type CELL represent single machine locations and are treated in a straightforward manner.

The production operands form the main link between the syntax (production) phase of translator (cf. Section II) and the semantic phase being discussed here. The definition is:

<production operand> :: = LEFT1 | LEFT2 | LEFT3 | LEFT4 | LEFT5 | RIGHT1 | RIGHT2 | RIGHT3

The operands LEFT1 - LEFT5 refer to the main stack before the production has been executed. The element at the top of the stack is always referred to as LEFT1. The operands RIGHT1 - RIGHT3 name the top three positions in the main stack after the execution of the same production. As we recall, each position in the main stack is actually two machine words, one which names the syntactic construct and the other which describes its meaning. The purpose of the stack operands is to enable the language designer to use or alter the semantics of constructs as they are recognized by his productions.

A simple example may be found in Appendix B on the line labeled B3. At this point in the syntax, an 'IF CLAUSE' of the small language has been recognized. The semantics of the 'IF CLAUSE' is the same as that of the boolean expression in LEFT2; namely a location to be tested for TRUE or FALSE. The action field in the production B3 contains a call of the routine 21↓. We see that in Appendix C, 21↓ consists of the statement

21↓ RIGHT1←LEFT2 ↓

This routine specifies that the semantics of the construct which was second from the top of the stack when the production was matched is to be assigned as the semantics of the element which is on top of the stack after production has been executed. We will see later that stack operands are also used in more sophisticated ways.

The next type of operand to be discussed is the compile time temporary or COMT. They are available as temporaries to the FSL user and

and are also used for communication with compile time routines. The character '␣' in the definition denotes a space and the <identifier> is assumed to be a subscript. This subscript can be either a constant or a variable of type CELL.

A similar construct is the run time temporary or RUNT. The RUNT's are system cells extant at run time and will be used for communication with run time routines. The subscript on a RUNT must also be a constant or a CELL. Since RUNT's exist only at run time they may not occur outside code brackets except in the form LOC [RUNT i] (see III-E) which specifies the location at run time of a RUNT as an operand at compile time.

Because of the simplicity of the small language in the appendices, there is no use of RUNT variables. There are several uses of COMT variables, for example in 16↓, the cell COMT 2 is used to hold the address found in the table for the identifier. The use of the temporary is necessary because the table-look-up operation cannot occur within code brackets.

The final instance of operand is an arithmetic expression within the brackets '<' and '>'. These are called contents brackets and are used in FSL for indirect addressing. The value of the arithmetic expression is assumed to be an address and the operand is taken to be the contents of this address. Since the arithmetic expression may itself be an operand, the contents brackets may be nested. An example of the use of contents brackets may be found in 25↓ of Appendix C.

Two FSL constructs closely related to operands are the <primary> and the <boolean primary>. The distinction between the three concerns the contexts in which each is legal.

The primaries take on numerical values and are legal in connection with arithmetic operations. Boolean primaries take on logical values and are used accordingly. Operands are constructs which can be used in either of these ways. We will first describe the various primaries and boolean primaries and then discuss the properties which they have in common with operands.

The primaries in FSL are described by the following formal syntax:

```
<primary> ::= <operand> | <constant> | (<arithmetic>) | LOC [<table id>] |
                   LOC [<stack id>] | <system cell> | <flad>
       <system cell> ::=  CODELOC | STORLOC | TEMPLOC
```

The first element of the definition indicates that any operand may be used as an arithmetic primary. A constant used in an FSL program will become part of the translator being described. Constants are expressed in the same way as ALGOL 60 constants [/].

The syntactic definition of a parenthesized arithmetic expression as a primary also follows ALGOL 60. This is needed to incorporate the usual grouping rules connected with arithmetic operations and will be discussed in III-E.

As we mentioned in Section III-C, both tables and stacks are implemented using a pointer to the next available location in their reserved storage areas. These pointers are used as operands of the form LOC [<table id>] and LOC [<stack id>] respectively. The value of either of these operands is an address and must be used accordingly. Following the usual convention, the pointers to STACK or TABLE operands cannot occur within code brackets. Similarly, since the pointers to RSTAK's and RTABL's are non-existant at compile time they cannot be used outside code brackets. The pointer to the symbol table, LOC [SYMB], is used as an operand in routines 2↓ and 29↓ .

The system cells mentioned as the next instance in the defintion of primary are also pointers. The cell CODELOC contains the address into which the next word of the compiled code will be placed. CODELOC is used by the system and is incremented as code is compiled. In addition, the language designer could use CODELOC in connection with his translation of labels, conditionals or subroutine definitions.

STORLOC is the pointer to the next available storage location for a particular source language program. It is used by the Storage Allocation Routine in the system and may also be accessed by the FSL user. In the semantics of the small language (Appendix C) the value of STORLOC at the beginning of each block is saved by 2↓. Then at the end of each block, STORLOC is reset to its previous value by 29↓. Since the Storage Allocation Routine is not used in the small language, STORLOC is also used in assigning storage to real variables (4↓) and boolean variables (5↓) as they are declared in a small language program.

```
4↓ TO←STORLOC; SET[TO,DOUBLE]; ENTER[SYMB;LEFT2,TO,REAL,LEV];
   STORLOC←STORLOC+2
```

Notice that in 4↓ STORLOC is increased by two to allow space for a double precision number.

The cell TEMPLOC is also used by both the system and the language designer. It points to the next in the list of temporaries used by the system in translating complicated expressions. In the small language semantics, conditional boolean expressions have been implemented using TEMPLOC explicitly in 22↓. In most source languages the FSL user would like to reinitialize TEMPLOC whenever values stored in temporaries would no longer be needed. In the small language this is done at every assignment statement (16↓, 20↓, 24↓). The cell T3 was assigned the initial value of TEMPLOC in 0↓.

The last alternative in the definition of <primary> concerns floating addresses or FLAD's. The syntax is

<flad> :: = FLAD1 | FLAD2 | FLAD3 | FLAD4

The flads are used to help implement undefined forward references, such as those occurring in conditional statements. When a flad is used as the operand of a transfer command appearing in an FSL statement, the system notes that an address will have to be added to that statement. When the proper place in the source program is reached an ASSIGN statement (cf. III-F) should be used. The system will then put the address into the transfer command and free the flad for further use. Each of the flads is actually a pushdown stack so that uses of flads may be nested.

Consider the example of the conditional statement in the small language. Routine 3↓ is called whenever an 'IF CLAUSE' which is part of a conditional statement is scanned.

```
3↓   PUSH[FLAD1,0]; CODE( ¬LEFT1 → JUMP[FLAD1]$) ↓
```

If the value at run time of the associated boolean expression is FALSE, the next statement is not executed. In terms of a translator -- a transfer around the statement must be compiled. Since the length of the statement is unknown at this point, 3↓ contains a JUMP[FLAD1] in code brackets. When the end of the statement is found (7↓) the current value of CODELOC is assigned to FLAD1 by the statement ASSIGN [FLAD1].

If the small language conditional statement had included an ELSE the flow would have been through 6↓ and 27↓ and would require two flads. Notice that each flad is used in a PUSH command before it is used as an operand. This allows for nested conditional statements in a small language source program. The ASSIGN command automatically does a POP of the flad after assigning it.

There are more boolean primaries in FSL than in conventional programming languages because of the nature of the translation task. While generating each individual piece of object code is not difficult, the job of choosing the right piece of code for each stage of the translation is quite involved. The variety of boolean primaries in FSL should alleviate the burden of determining the state of the translator. The syntax is:

```
<boolean primary> ::= <arithmetic> <relation> <arithmetic> | <operand>|
                      (<boolean>) | TRUE | FALSE | SIGNAL | OK | TEST
                      [<arithmetic>,<data id>] | CONST [<arithmetic>]
```

The relations defined in FSL are '=' , '≠' , '>' , and '<' . These all have their customary meanings and are defined both inside and outside of code brackets. The second instance of <boolean primary> is the type <operand> described at the beginning of this section. Thus any construct of type <operand> may be used in either a boolean or an arithmetic context. The definition of a parenthesized <boolean> as a <boolean primary> parallels the situation with arithmetic expressions. Both will be discussed in the next section.

The logical constants, TRUE and FALSE are also boolean primaries. They may occur either inside or outside of code brackets. The cell, SIGNAL, is set TRUE or FALSE by various routines which are part of the system. For example, if the routine to select an operand from a table cannot match its entry, SIGNAL is set FALSE. The status cell, OK, is set by the language designer and used by the system. If OK is FALSE, no code will be generated for the source program being scanned. The FSL user can set OK in the event of a non-recoverable source language error. Even if OK is FALSE, syntax checking will continue until a halt command is given. There is no way to reset OK once it has been given the value FALSE.

The next instance of <boolean primary> is the TEST statement, which involves data types. As we mentioned in Section III-B, FSL allows the declaration of tags which can be placed into a computer word. The value of a TEST is TRUE if the location specified by its first parameter contains the bits corresponding to the <data id> which is its second parameter. Further information on the use of data types in FSL will be provided in Section III-E.

The final instance of boolean primary is the test for constants, CONST[<arithmetic>]. The arithmetic expression is assumed to specify a location to be tested. CONST will have the value TRUE if the location being tested contains a numerical or logical constant. This test is necessary because the FSL system is set up to process constants directly when used in normal mode. In the small language, we test for constants when an identifier is used in an arithmetic expression (8↓, 9↓). If the identifier has the semantics of a constant, no action is necessary. Otherwise the identifier is a variable and must be looked up in the symbol table, SYMB.

```
9↓ CONST[LEFT1]→ RIGHT1← LEFT1  :
   SYMB[LEFT1,,$,]= REAL→RIGHT1←SYMB[LEFT1,$,,]:FAULT 1$$ ↓
```

Of the boolean primaries, OK, SIGNAL, and CONST are meaningful only at compile time. These may appear outside code brackets only, while the other boolean primaries can occur either inside or outside of code brackets. Although the arithmetic primaries and operands exist only at compile time, there is a special convention that allows most of these to appear within code brackets.

This is possible because the usual value at compile time of an arithmetic operand is an address. Thus while, for example, CODELOC exists only at compile time, it contains an address which is itself meaningful at run time. For these reasons, we have adopted the convention that the occurrence of a compile time cell within code brackets specifies that we use the compile time contents of that cell as the operand of the code to be compiled.

A simple example will help clarify the situation. In 12↓ the expression

```
LEFT4  +  LEFT2
```

appears within code brackets. Assume that, as will usually be the case, both LEFT4 and LEFT2 contain addresses at compile time. If the the expression above were not enclosed in code brackets, the two addresses would be added at compile time to produce another address. When the addition occurs within code brackets an entirely different action takes place. In this case the system will generate code to do an addition at run time. The addends at run time would be the run time contents of the addresses contained in LEFT4 and LEFT2 at compile time.

The process described above may be thought of as adding an extra level of indirectness to compile time operands occurring within code brackets. Since the convention holds for most operands and arithmetic primaries, we will point out the exceptions.

This convention obviously cannot apply to RUNT's which do not exist at compile time and only appear inside code brackets. It also does not apply to table and stack operands extant at compile time because these implicitly involve compile time actions. In addition, FLAD's are a special type of operand to which the convention does not apply.

As we will see, the above convention is part of the overall rule that all operators appearing within code brackets specify run time actions. Another example of this concerns contents brackets. Any occurrence of contents brackets within code brackets specifies indirect addressing to be done at run time. More explanation and examples of this situation will be presented in the next section, which deals with the construction of expressions in FSL.

E. Expressions

There are two kinds of expressions, arithmetic and boolean, in FSL. The description of expressions in this section assumes an understanding of Section III-D, which deals with operands and primaries. Each FSL expression is formed by combining the appropriate primaries with a simple set of operators.

The arithmetic expressions in FSL appear in the syntax more frequently than any other syntactic type. This is largely because addresses at compile time are of this type. The syntax of arithmetic expressions is:

```
<factor> ::= <primary> | <factor> ↑ <primary>
<term> ::= <factor> | <term> * <factor> | <term> / <factor>
    <arithmetic> ::=  <term> | < ± > <term> |
                      <arithmetic> < ± > <term> | INT [<arithmetic>] |
                      ABS [<arithmetic>] | LOC  [<arithmetic>] |
                      CHAIN [<arithmetic>]
```

The practice of breaking up the definition of arithmetic expressions into parts follows the ALGOL 60 report. This notation is a convenient way to represent the normal grouping rules of arithmetic. The operator '↑' represents exponentiation which actually implemented by a subroutine. The definition of the other arithmetic operations is straightforward.

The one potential source of difficulty is the proper use of code brackets. Any occurrence of an arithmetic operator within code brackets specifies an action to be performed at run time. This implies that all computations on addresses must occur outside code brackets.

Since the arithmetic operations in the small language include only those operators treated directly by the system, the examples (10↓- 14↓ , 28↓) in Appendix C should be clear. Each of these routines carries out code generation for one of the basic arithmetic operations. The use of VALUE operands in these examples will be explained in the next section.

In addition to the operations described above, there are four other ways of describing an arithmetic expression. The value of INT [<arithmetic>] is the largest integer which is not greater than the value specified by the <arithmetic>. This function is identical to ENTIER described in the ALGOL 60 report [31]. The value of ABS [<arithmetic>] is the absolute value of the operand specified by the <arithmetic>. Either of these can appear inside or outside of code brackets describing actions to be taken at run time or at compile time, respectively.

The LOC operations is used with two slightly different meanings in FSL. If the operand of LOC is a stack or table identifier, LOC will have the appropriate pointer as its value (cf. Section III-C, III-D). Any other use of LOC describes a reduction in the indirectness of the addressing of its operand. In this case LOC acts as the inverse of the contents brackets '<' and '>'.

The use of CHAIN as a unary operator is more involved. The CHAIN of an arithmetic expression is used when some operand, usually a label, is used before its value is defined. An example of this may be found in 25↓ of the Appendix C. If the label in a 'GO TO' statement of the small language is undefined, the tests in 25↓ lead to the statement

```
CODE (JUMP [CHAIN [COMT 2] ] )
```

This command will cause the system to compile a jump command with the address portion to be specified later. The cell COMT 2 contains the location in the SYMB table where the address associated with the label is to be stored. If there are several uses of the same undefined label the system will build a linked list or chain to keep track of them. Then when the label is defined (26↓) an ASSIGN statement would be used. This will cause the system to fill in all previous references to the undefined label, including the one in SYMB. We will have more to say about ASSIGN in Section III-F. An appearance of CHAIN outside code brackets, is meaningless since the system automatically handles all undefined references in an FSL program.

The syntax of boolean expressions also consists of several steps. This is set up so that the following equivalence holds for boolean expressions:

$$\neg A \wedge B \vee C \wedge D \equiv ((\neg A) \wedge B) \vee (C \wedge D)$$

In other words '¬' binds most tightly, then '∧' and finally '∨'. The syntax is:

```
<boolean factor>  :: =  <boolean primary> | ¬<boolean primary>
<boolean term>  :: =  <boolean factor> | <boolean term> ∧
                      <boolean factor>
<boolean>  :: =  <boolean term> | <boolean> ∨ <boolean term>
```

All boolean expressions may take on only the values TRUE or FALSE. Since the value of a compile time boolean expression is never an address, these may never occur within code brackets. The boolean operations themselves may occur within code brackets, specifying logical operations to be performed at run time. Boolean expressions are most often used in connection with conditional statements which will be discussed in the next section.

F. Statements

The statement types in FSL include most of the usual constructs found in programming languages. The unconditional statements are formed according to the following rules

```
<unconditional>  :: =  <storage> | <assignment> |
                       <transfer> | <auxiliary> |
                          CODE (<unconditional>)
```

The storage statements are

```
<storage> :: = <stack command> | <enter>
```

These were discussed in detail in Section III-B and III-C.

The assignment statement in FSL is more general than that usually found in programming languages. The syntax is:

```
<assignment> :: = <left side> ← <arithmetic>
                  <left side> ← <boolean>
<left side> :: = <primary> | VALUE1 | VALUE2   VALUE3
```

Notice that the left side of an assignment statement can be any arithmetic primary, rather than just an identifier. This proves useful in translator writing, where addresses are often computed befor being stored into. One must be careful in using this feature inside code brackets. Any address computation inside code brackets will be done at run time.

The use of a VALUE word as the left side of an assignment statement requires more explanation. Consider the semantic routine 10↓ in Appendix C, which is called whenever a multiplication in the small language is recognized.

```
10↓  CODE (VALUE2 ← LEFT4 * LEFT2)↓
```

We can see from the productions that the operands of the multiplication are second and fourth in the stack. Thus LEFT4 * LEFT2 in code brackets will cause the code for the multiplication to be compiled. The problem is that we will want to use the result of this multiplication in some future operation. This is handled in the syntax by putting the symbol 'T' into the second position of the syntax stack. The purpose of VALUE2 is to assign semantics to the 'T' which represents the results of the multiplication. It is important to note that the semantics is filled in at compile time. This represents the only deviation from the convention on operators inside code brackets and the special VALUE operands mark this fact. A store into VALUE1 inside code brackets has the same effect as a store into RIGHT1 outside code brackets.

The next type of statement to be considered is the jump or transfer statement. The syntax is:

```
<transfer> :: =  JUMP [<arithmetic>] | JUMP [<label>] |
                 MARKJUMP [<arithmetic>] | MARKJUMP [<subroutine>] |
                 EXECUTE [<arithmetic>].
```

The JUMP statement is the well known unconditional transfer of control in a program. If the operand is an arithmetic expression it is presumed to specify the address to be transferred to. Since an FSL user has no knowledge of absolute address in his translator, computed transfers can occur only within code brackets. Transfers outside of code brackets are done with labels (in the translator itself). Any FSL statement can be labeled and a transfer can be made to any labeled statement. No label may occur within code brackets, but bracketed statements can be labeled.

The MARKJUMP command specifies a return-jump or subroutine-jump to its operand. If a MARKJUMP [β] occurs in location α two distinct actions take place: First the address α + 1 is put in location β and then control passes to location β + 1. As with JUMP, a MARKJUMP to a computed address can occur only within code brackets. The operation MARKJUMP [<subroutine>] can occur either inside or outside of code brackets. These call various subroutines which are part of the FSL system. Calls of run time subroutines appear inside code brackets and calls of compile time routines occur only outside code brackets. The system subroutines will be described in Section IX.

The EXECUTE command requires an <arithmetic> as its operand and thus occurs only within code brackets. An EXECUTE will cause the command in the location specified to be executed and control to be returned to the statement following the EXECUTE. This is the same as a MARKJUMP to a subroutine of one instruction. The EXECUTE command is useful in sharing the code for two slightly different routines.

The auxiliary statements in FSL include a number of different types of commands which do not fit into the other categories. The syntax is:

```
<auxiliary> :: = SET [<arithmetic> , <data id>] |
                 CLEAR [<arithmetic>] | FAULT   <identifier> |
                 STOP | TALLY  [<arithmetic>] | MINUS [<arithmetic>]
                 | ASSIGN [<arithmetic>].
```

The SET and CLEAR statements are used in tagging and removing tags from addresses. Both are discussed in III-C where it is shown that neither can appear inside code brackets. The FAULT statement enables the language designer to provide error messages in the event of a semantic error. For example, in 8↓ Appendix C, it is a FAULT if an identifier used arithmetically has not been declared REAL.

```
8↓  CONST[LEFT2] → RIGHT2 ← LEFT2 :
    SYMB[LEFT2,,$,]= REAL → RIGHT2 ← SYMB[LEFT2,$,,]:FAULT 1$$ ↓
```

After printing the message 'FAULT 1' the system will return to the next statement. In some cases one might then want to set OK to FALSE, eliminating all further code generation.

In any event, once a FAULT has been executed the system will not run the source program which had the semantic error.

The statement STOP may occur either inside or outside code brackets. When a STOP is executed the entire program will be stopped. A STOP outside code brackets will stop the translator, while a STOP inside will stop the running program. There is an action HALT in the production language (entirely distinct from FSL) which causes translation to cease and execution of the compiled program to commence.

The commands TALLY and MINUS are merely shorthands for arithmetic statements. TALLY means add one to the operand specified and MINUS means subtract one from the operand. Either may be used inside or outside of code brackets and can lead to more efficient code. There are several instances of TALLY and MINUS in Appendix C.

The ASSIGN statement is used in connection with CHAIN and with FLADS. In either case the parameter to ASSIGN is the address of the head of a linked list. On this list are all the past references to the entity being assigned. ASSIGN has the effect of filling in the current value of CODELOC as the address portion of all these commands. If the parameter named a FLAD, a POP is then executed. For more information on chaining and forward references see Sections III-D and III-E. In Appendix C, routines 6↓, 7↓, and 27↓ handle the assigning of flads while chained labels are assigned in 26↓. An ASSIGN statement cannot appear within code brackets.

All of the statements described above were of the type <unconditional>. Except as noted, any of these may appear inside or outside code brackets. We also define a sequence of statements:

```
<statement sequence> :: =  <statement> |
                           <statement sequence> ; <statement> |
                           CODE (<statement sequence>)
```

We may also combine statements with boolean expressions to form conditional statements. The syntax is:

```
<conditional> :: = <if clause>  <statement sequence> $ |
                   <if clause>  <statement sequence> :
                        <statement sequence> $ |
                   CODE (<conditional>)
<if clause> :: = <boolean> →
```

The two types of conditionals correspond to the ALGOL 60 conditional statements with and without 'ELSE'. By requiring the special punctuator '$' to terminate all conditional statements, FSL is able to permit great flexibility in the construction of the two statement sequences. Either the 'true' part or the 'false' part of a conditional statement may be any sequence of FSL statements including other conditionals. This seems to be more convient than other schemes considered for conditionals.

If a conditional statement appears inside code brackets, the tests and transfers will all be compiled. If not, the sequence of statements in either part of a conditional may still contain any combination of bracketed and unbracketed statements.

There are several occurrences of conditionals outside code brackets in Appendix C. For example, routine 8↓ contains a set of nested conditional statements. For examples of both types of conditional statements within code brackets see routines 3 ↓ and 22 ↓. In these latter routines all the tests and transfers required will be put in the running program.

Any FSL statement may be prefixed by a label. The syntax is:

<statement> :: = <unconditional> | <conditional> |
'<label>' <statement>.

As was mentioned at the beginning of this section, labels may not occur within code brackets. The quotation marks set off the label in the FSL program and are not used when the label in the operand of a JUMP command. These labels are internal to an FSL sentence and should not be confused with integer names linking the semantics with the productions of Section II.

G. Subroutines

Subroutines appear in many forms in FSL. In this section, we will discuss the use of subroutines which are part of the system itself. To implement subroutines in a particular source language, one would use the MARKJUMP command described in Section III-F.

All of the source languages described in FSL will have access to a set of library subroutines. The library will be expandable, but will contain at least the subroutines described in the syntax.

<subroutine> :: = SIN | COS | LOG | EXP | SQRT | ARCTAN | SIGN

To process a call on one of these routines the language designer will use the systems run-time cells, the RUNT's. Each library routine expects to receive its parameters in RUNT 0 ... RUNT n where n+1 is the number of parameters involved. The value of any system subroutine will be left in RUNT 0.

After putting the parameters into the RUNT's the proper subroutine must be called. Library routines are called by a statement of the form

MARKJUMP [<subroutine>].

The library subroutines are available only at run time and thus any call on a library routine must occur within code brackets.

In addition to the library routines, there are some subroutines which are part of the system at compile time. The purpose of these routines is to relieve the FSL user of handling the details of some complex operations executed at compile time.

We have already encountered some examples of compile time routines in the discussion of tables in Section III-B. The operations of entering data into tables and of retrieving it from them were described as implicit subroutine calls. The one explicit call of a compile time subroutine is used in connection with the allocation of a storage in a source language program.

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The task of allocating storage and building access functions for complicated data structures is among the most difficult to be found in translator writing. There is in FSL a Storage Allocation Routine, SAR, which helps the designer solve this problem. In its present form, the SAR is capable of handling rectangular arrays of any dimension whose elements are all of the same precision.

The SAR expects a description of the data structure to appear in the compile time temporaries, the COMT's. The contents of COMT 0 will be a '1' if storage for an array is desired and should be '0' if a simple variable is to be allocated space. The contents of COMT 1 should be the number of words per element (precision) of the array and COMT 2 the number, n, of dimensions of the array. The next 2n COMT's will contain the lower and upper limits for each dimension of the array. Each of those must be a positive or negative integer which is fixed at compile time.

After all the parameters have been filled in, a statement of the form

MARKJUMP [SAR]

should appear in a semantic routine. The SAR will then allocate storage for the array and build an access function for later use. The SAR will leave an integer in COMT 0 when it is finished. This integer is the internal name of the array and will presumably be put into a symbol table.

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When a reference to an element in the array occurs in the source code another compile time routine, PLACE is executed. This routine compiles code to generate the proper element of the array as an operand at run time. Like the table operand, this operand involves an implicit call of a compile time routine. However, certain information must be in the COMT's before the use of a storage retrieval statement.

The contents of COMT 0 should be the internal name of the array supplied by the SAR. It should be set to the data type of the array element (cf. Section III-B). If the array was n dimensional, the next n COMT's will describe the subscripts of the array element. Each description of a subscript is of one of two types. If the subscript appears in the source code as a constant, the constant itself will describe the subscript. If the subscript is to be computed, information on where the value of the subscript will be at run time will be provided in the COMT's. If the language designer uses the main stack in the usual way, this distinction is not important to him. His statements would probably be of the form

COMT 3 ← LEFT2, etc.

After the subscripts have been described a retrieval routine must be called. The purpose of this routine is to compile the code which will access the array element. To the FSL user, what is important is the address of this element, which will be used in compiling more code. A statement of the form

```
CODE (VALUE1 <— LOC [PLACE])
```

will produce code to find the location of the element and will also put the appropriate information in the stack at compile time. The information is placed in the desired stack position by using the appropriate VALUE operand as described in Section III-D.

Notice that the statement above will leave a description of the location of the array element in the stack. This is useful for multiple precision arrays where a number of operations may be performed on the several successive locations which comprise the array element. To retrieve the array element in normal addressing mode, one would use a statement of the form

```
CODE (VALUE1 <— PLACE)
```

which will leave the description of the array element in the stack with the normal addressing mode. Since PLACE involves actions both at compile time and at run time, it is a special case and may only occur as described above.

The use of the SAR and of PLACE as described above is so complicated that one might question its usefulness to the language designer. There is a system cell, STORLOC, in FSL which points to the next available storage location and is used by the SAR. The language designer can do his own storage allocation using STORLOC and, in fact, this is done in the small language where there are no subscripted variables. It seems likely that the problem is intrinsically complicated and that no simple algorithms for array accessing exist.

There is another reason for using the system routines in storage allocation. Subscripting is often done quite differently on different computers. The relative efficiency of using index registers or other special features is a consideration best left to the system as it functions on a particular machine. The description above specifies no particular implementation. It is also expected that the SAR will eventually include provision for other data structures such as linked lists and files. The main reason these were not put in is that there is as yet no precise and generally accepted operational definition of either construct. The FSL system is set up so that more system subroutines can be easily added if the need arises.

H. Program Structure

Any program in FSL is the complete semantic description of some programming language. This description is also the specification of a translator for that language. Structurally, an FSL program consists of two separate parts, a declaration part and the main body.

The declaration part of an FSL program describes the storage to be used by the translator. The several types of storage were discussed in Sections III-B and III-C. The syntax is:

```
<declaration part> :: =  <declaration> |
                         <declaration part> ; <declaration>
<declaration> :: =  <table dec> | <stack dec> | <cell dec> |
                    <title dec> | <data dec>
```

All of the declarations must occur together at the beginning of an FSL program. The remainder of the program consists of the semantic description of individual constructs in the source language.

These semantic descriptions of source language constructs are linked to the syntax (productions) by means of statement numbers. Each numbered semantic routine corresponds to an action 'EXEC' appearing in the syntax of the source language. Those semantic descriptions are combined with the declarations to form the semantic description of a particular source language. The syntax is:

```
<semantic program> :: =  <program head>  END
<program head> :: = BEGIN <declaration part> ; <sentence> |
                    <program head> ; <sentence>
<sentence> :: =  <integer> ↓ <statement sequence> ↓
```

The construct <statement sequence> has been discussed in III-F. The <integer> is the statement number mentioned in the preceding paragraph. The complete formal syntax of FSL may be found in Appendix D.

In its present form, FSL includes no constructs for formally describing input-output operations. We have chosen, rather, to include a common input-output language in each source language in the system. This input-output language is very similar to the one described by Perlis [32].

This approach has been taken for several reasons. It seems to be in the nature of input-output languages that they depend more on hardware than on the source language into which they are imbedded. Requiring each language designer to specify a complete format language for his translator would contradict the aim of the project. In the current system, the language designer need worry about input-output only at a very superficial level.

To imbed the entire input-output language in a source language, the FSL user must make two additions to his formal description. In the syntax (productions) of the source language, he must check for the occurrence of certain special characters. The appearance of one of these characters specifies that the following source code is a format description. Upon the scanning such a symbol the productions of the source language are expected to execute a transfer to a predefined label. In addition, the user must place a predefined label on the production to be executed at the end of a format statement.

The second addition to the source language description occurs in the semantics. A format statement specifies how a construct is to be printed or read but does not determine which machine location is to hold the data. There is, in FSL, a special run-time stack, NAME, in which the input-output processor expects to find this information. In his semantic description, the FSL user must have a statement which fill the stack NAME with the locations to be processed by the format routines.

With these two additions to a source language description, the designer buys the full power of a sophisticated input-output language. The format language is now available only in the source languages, but could easily be added to FSL itself if this proved desirable. The 'easily' results from the fact that the system has been implemented in such a way that the Basic Compiler and the FSL translator are very similar. A discussion of how this similarity was attained and the advantages it provides are contained in the next section.

IV. IMPLEMENTATION

The formal semantic language described in the previous chapter was originally developed with no implementation in mind. Once a complete and precise formalism was described, it was felt that it could easily be put on the machine. While it had been planned to stop short of implementation, we were moved to implement precisely because so many other efforts had stopped at just this point. Predictably, the nature of the formalism underwent many changes during implementation.

When, in August of 1963, we became committed to implementation, the natural first study was of translators already running on the Carnegie Tech computer. The hope was that we could adapt an existing compiler to the task of building a compiler-compiler. There were two reasons for choosing this path rather than starting afresh. Obviously, this method would be quicker and easier. The second reason was that part of the theory behind the system states that many translation tasks are independent of the language being translated and thus an existing translator should suffice.

At this time the Carnegie Tech ALGOL compiler [13] was just beginning to operate as a full-fledged running system. The syntax phase of the ALGOL translator was based on a version of Production Language and operated in an almost language-independent fashion. There were two difficulties involved in using the ALGOL syntax phase. The productions used for ALGOL were based on the conversion of the source code into a Polish postfix intermediate language. Further, this result was achieved by using a hierarchy table to implement the binding rules for the various ALGOL operators. The problem was that neither of these techniques was easily adaptable to a general purpose translator.

With great ingenuity, A. Evans devised a scheme whereby such ALGOL separators as FOR, ELSE, and WHILE would fit into the postfix form and the hierarchy system. We were loath to require such ingenuity of every designer using our system. Besiders, we felt that an intermediate language such as postfix would add complexity to a system that already threatened to become unmanageable.

The solution to these two problems are interrelated. Instead of hierarchies we have implemented grouping rules by changing the names of constructs in the syntax stack. This technique is in essence inverting the BNF grammar and is described in Section II-A. This technique is easy to use and has the additional advantage that it is fail-safe. As each construct is recognized by the productions an appropriate action is taken. If a construct would lead to the generation of code, this code is built at the time the construct is recognized.

Fortunately, the implementation of these changes required relatively minor alterations in the ALGOL production loader. These were carried out and we were then in possession of a general purpose syntax phase. As we have mentioned in Section I, the syntax of a source language is handled in two steps. The productions of the source language are fed into the Syntax Loader which produces from them a set of tables. These tables are then imbedded in the Basic Compiler and determine the syntax phase of a translator for the source language.

This syntax technique had one marked advantage over previous table driven compilers. Since the productions were recognizer-oriented and non-recursive the syntax phase of the translator could be executed quite rapidly. The slow operation of recursive recognizers had even led to statements that no general purpose recognizer would ever be efficient. Although this difficulty was now overcome the real problem was getting a general purpose system to produce code.

Part of the code generation problem is no more difficult in a compiler-compiler than in conventional translators. Individual pieces of code are usually generated by small special purpose routines. For example, there might be a generator for addition and subtraction statements, one for transfers and one for conditionals. The nature of these generator routines depends very little on the source language being translated. However, if the code produced is to be at all efficient, the generators must have a great deal of information about in-transit states of the translator during the code production process.

Since we would be trying to generate code directly from the main stack, it was convenient to keep much of the information in the stack.

This was accomplished by having each element of the stack consist of two machine words. The first of these two words holds the syntactic type of the element in the stack and is used by the syntax phase in matching productions. The second word contains the semantics of the construct in the stack and is used by the code generators. In an FSL language description, a reference to LEFT3 specifies the second word of the element in the third position of the main stack.

The basic unit of information in any compiler is a machine address. The semantic word in the main stack normally consists of an address and some identification bits. The following table shows the use of the G-20's 32-bit word in describing an operand. In all cases the bit is set if the predicate is true.

Bit	Use
0 - 14	Address
15	Integer Constant ?
16	Floating Constant ?
17	In Accumulator ?
18	Floating Address (FLAD)?
19	In a Temporary ?
20	Negation (Arithmetic or Logical)?
21 - 24	Data Type: LOGIC, INTEGER, ...
25	COMT ?
26	RUNT ?
27 - 29	Addressing Depth (0 - 7)
30 - 31	Interrupt Flags

Figure 3.

It is not within the scope of this paper to explain how all of this information is used by generators to produce G-20 machine code. What is of interest here is that the language designer using FSL need not deal directly with the complex problem of code generation. For example, consider the statement describing the addition of two numbers in the small language (12↓ of Appendix C)

12↓ CODE(VALUE2 ← LEFT4+LEFT2) ↓

When a production with the action 'EXEC 12' is matched, an addition is to be compiled. Using the information in the stack positions LEFT4 and LEFT2 the system is able to compile locally optimal code from the designers simple semantic statement. For example, one of the operands may already be specified as being in the accumulator at run time. If one operand is of the wrong sign a 'subtract' or 'reverse subtract' command must be compiled. These and many other tests are handled automatically by the system. In short, any local optimization techniques available on a particular computer should be feasible in an FSL system.

The significance of VALUE operands should now be much clearer. In processing an addition statement using 12↓ , one not only must generate code but must also assign semantics to the position in the main stack which is to hold the result. After the addition has been processed the result is to be placed in the second stack position, hence VALUE2. In this case RIGHT2 will have the syntactic type 'E' and semantics specifying that its value will be in the accumulator at run time. Should the system need the accumulator for another computation, it would automatically compile a 'STORE' command and change the semantics of 'E' to indicate that its value will be in a temporary.

The writing of generators and auxiliary routines to use this semantic information was not very difficult. The complex problems arose in trying to build the semantic descriptions. The goal was to establish a system whereby the proper semantic information could be assembled with as little effort as possible on the part of the FSL user. To discuss this topic we must present the third basic program in the system, the Semantic Loader.

As we mentioned in Chapter I, the system consists of a Production Loader, a Semantic Loader and a Basic Compiler. We present the Semantic Loader last because, in a sense, we have already discussed its essential properties. The semantic meta-language, FSL, is a well-specified programming language and thus its syntax is expressible in Production Language. This Production Language syntax could then serve as the basis for an FSL translator. The Semantic Loader is built in precisely this way -- the productions for FSL constitute Appendix E of this paper.

These productions were processed by the Production Loader which produced a set of syntax tables to be used by the Basic Compiler. These productions had calls on semantic routines just as those in source languages. The semantics of FSL, however, were written in G-20 assembly language. In addition, some minor changes were made in the Basic Compiler to facilitate its use as a special purpose translator. We will discuss the question of writing the FSL semantics in FSL in the next chapter.

Many interesting problems arose in coding the semantics of FSL. We were attempting to compile efficient programs which would in turn compile efficient programs. One of the greatest difficulties was keeping track of the level at which each action was to occur. To aid in this distinction we use the terms meta-compile time, compile time, and run time. It is important to remember that communication goes only one way in this chain. We will not permit situations where the compiler must refer to the meta-compiler for information in processing a piece of source code.

As one might suspect, the main stack in the Semantic Loader is arranged just as that of the compiler described at the beginning of this chapter. This means, among other things, that the same optimization techniques are available at both levels. This reflects the basic tennant of the design philosophy that the Semantic Loader and the Basic Compiler be as similar as possible.

Keeping these two programs nearly identical was a key step in the implementation of the system. To see why this was important, we must consider the function of the Semantic Loader. The semantic description of a source language will specify some actions to be performed at compile time and some to be executed at run time. The semantic loader will generate code (for the compiler) to execute compile time actions and will produce calls on compile time generators to build the code for actions to be performed at run time. In other words, any FSL operation occurring outside code brackets will lead to meta-compile time generation and compile time execution of code. An operation that appears within code brackets will be processed by a compile time generator and be executed in the running program.

It should now be easy to see the advantage of keeping the Semantic Loader and Basic Compiler similar. In our system, the two programs shove the same basic generators, auxiliary routines, and tables. To simplify matters further, the Semantic Loader builds code for the compiler in the same locations as that code will occupy at compile time. Considerable pains were taken to have addresses coincide in the two programs so that symbolic addresses could be used in the Semantic Loader and the correct absolute addresses would appear in the semantic tables.

From the discussion above it should not be difficult to understand the operation of the processors for the usual arithmetic and boolean operations. Many of the other FSL constructs have no counterpart in the compiler and are thus handled non-uniformly in the Semantic Loader. We will discuss some of these to show how the system operates. In view of the table in Figure 3. it should be easy to discern the implementation of the various operations on DATA variables: SET, TEST, CLEAR. Each of these leads to the appropriate bit commands on the data type field (bits 21-24) of the specified operand.

Similarly, the indirect addressing operations effect bit operations on the addressing level portion (bits 27-29) of a word. The predicate CONST leads to a test for the presence of the bit marking a constant. All of these operations are built into code for the compiler. Some of the more complicated operations are implemented by calls on compile time subroutines.

When a compile time routine was used to implement an FSL construct, considerable effort was used to take advantage of the special features of the G-20. Such operations as entering data into tables and retrieving it from them involved fairly complex subroutines at compile time. The handling of chaining and FLAD's was also done with closed routines. The calls for these compile time routines are processed exactly as calls on generators. The only serious difficulty in this process concerns the description of operands for the compile time generators and routines.

Like all high level programming languages, FSL depends on a great deal of implicit information. Each operand occurring in an FSL statement will be translated into a 32-bit semantic word, (see Figure 3.) at meta-compile time. If the operand is to be used by a compile time generator or routine, the appropriate semantic word must be built at compile time. The routine to make meta-compile time descriptions into compile time ones is as complicated as any in the system. If the operand is a constant, its description at compile time is the same as at meta-compile time. For RUNT or COMT variables, the semantic word specifies a subscript which might be fixed or variable. References to stacks, variables and FLADs are handled indirectly. The communication of addressing depth is also a problem. Thus if the contents brackets occur within code brackets, the indirect addressing is to be done at run time and this information must be given to the compiler. Further, there is an implied extra level of indirectness for compile time operands. Since all of these considerations are treated by the one operand preparation routine, the rest of the Semantic Loader is relatively straightforward.

The entire Semantic Loader was built in modular form. This modular organization was natural for a production-based translator and proved invaluable in the development of the system. As users discovered operations which would improve the system, these were added without changing the rest of the system.

One of the most valuable features of our implementation was its similarity to the ALGOL translator. The ALGOL system carries most of the usage load at Carnegie Tech and underwent considerable independent development during the course of this project. As various debugging aids were added to ALGOL, we were able to incorporate these in the FSL system at both the meta-compile and compile-time levels. The format language used in the FSL system is also closely modeled on the ALGOL format.

Because of these simplifying features, the entire implementation took less than six man months. The two basic components of the system are a syntax directed compiler and a Production Loader, each of which is used in two places. An ALGOL 60 version of the Production Loader will be available from A. Evans [12] later this year. Basing our system on existing programs involved certain compromises. The effect of these compromises will be discussed as part of the review and critique in the next chapter.

V. CONCLUSION

A. Review and Critique

In this chapter we will review the principal developments in the paper and point out both weaknesses and possible extensions of the system. The basic idea is that, through appropriate formalization, much of the difficulty involved in translating computer languages can be eliminated.

The formalization of semantics for computer-oriented languages requires that syntax and semantics be carefully separated. In Chapter I we defined notions of syntax and semantics and the concepts of syntax meta-language and semantic meta-language. After comparing our definitions with alternative ones, we described how a compiler-compiler, based on our definitions of syntax and semantics, could be organized.

Chapter II contained a description of the syntax meta-language, Production Language, used in our system. Section II-A was basically a users guide to Production Language as a programming language. The remainder of that chapter discussed some of the more abstract properties of syntax meta-languages with the emphasis on the properties of the Production Language. It was shown there that, under various restrictions, Production Language could be considered either as quite weak or as extremely powerful in comparison with other formal systems.

The longest and most important part of this thesis is Chapter III, which discusses the Formal Semantic Language (FSL). Although many syntax meta-languages have been developed over the years, FSL is the first attempt to provide an adequate semantic meta-language for computer-oriented languages. Many of the features of FSL are formalizations of techniques which have proved useful in translator writing. Among the more interesting constructs are the operations on tables and stacks and the facilities for handling indirect references. Probably the most important feature is the clear distinction between actions taken at translate time and those performed at run time. In Chapter III FSL was described strictly as a language for describing the semantic phase of translators.

The implementation of one general purpose translator was described briefly in Chapter IV. By making use of programs already running on the G-20, we were able to implement the system in a relatively short time. The most difficult problems were those involved in the interface between the three separate programs which comprise the compiler-compiler. Those problems were solved and many peripheral advantages gained by using a high degree of parallelism in the component programs.

One of the topics discussed in the earlier chapters was a set of criteria for semantic meta-languages. We mentioned that a semantic meta-language should be easy to use and should be readable so that others can understand the languages described in it. It should be sufficiently flexible to allow descriptions which can specify an automatic translator for any of a large and varied class of source languages. Further, a good semantic meta-language should be independent of any particular computer. An additional and very important consideration is the quality of translators produced by such a system.

The Formal Semantic Language, FSL, embodies an attempt to satisfy all these conditions. There is now considerable evidence that FSL is easy to write in and not too difficult to read. The justification of these statements is based on the author's success in teaching FSL to undergraduates.

The system was presented in an advanced undergraduate programming course at Carnegie Tech. None of the students in either term had any previous experience in translator design, but all had taken the equivalent of two semesters of elementary programming. The material presented in the course was the non-theoretical parts of Chapters II and III of this thesis. In the sixth week of each semester the students chose projects which would constitute the main part of their semester grade. Among the topics suggested were the construction of translators for some common programming languages.

The projects in the first term class were not completed on time, largely due to errors in the FSL system itself. These projects were of tremendous value in pointing out coding errors and conceptional weaknesses in the system. Many of the FSL constructs described here were first suggested by problems encountered in these projects. However, student interest in the project remained high and almost all enrolled for the second term so as to complete their projects.

During the second term the students had a much more stable system to work with. The course outline was accelerated to allow an earlier start on the term projects. Although the FSL system still was not completely debugged, the better students were able to complete translators during this term. A detailed presentation of these projects will be released later this year as a research report.

One of the interesting features of the second term class was the use of students as instructions. One hour a week was denoted to progress reports by students working on term projects. The discussions included detailed presentations of the formal syntax and semantics of the language under consideration. The class was usually able to follow the presentation in sufficient detail to suggest possible flaws in the translator being designed.

Of interest here is that a group of new programmers (undergraduates) were able to learn, use and expound the FSL system in a one term course. Besides learning the FSL system, the students were forced to consider and solve many of the unique, logically complex, and generally tedious problems involved in translator writing. The problems, such as local optimization of code, which are handled automatically by the system were discussed in supplementary lectures.

Among the translators attempted by students were ones for such diverse languages as ALGOL, LISP, FORTRAN, COMIT, and SIMSCRIPT. Not all efforts were equally successful, but it is difficult to determine whether the discrepancy is due to the difference between students or between languages. We can, however, make some remarks about the class of languages for which the FSL system is adequate.

The FSL system is for the description of languages which can be compiled, i.e., those for which the course of action can be fixed at translate time. If a language involves constructs whose meanings are not available until run time, one must, of course, use run time routines as part of a translator for this language. There are provisions for constructing run time translator routines in FSL, but they are not as convenient as they might be. For this reason, among others, LISP and COMIT were somewhat tricky to design.

The other difficulty in LISP and COMIT was the absence of fixed FSL primitives to act on linked lists. These were not put into the system because, as yet, there is no universally accepted way of representing and operating upon such lists. Similarly, the SIMSCRIPT effort was made more difficult by the absence of any good primitives for operating on data files. All of these difficulties can be overcome, but an ideal system would make them unneccessary.

A much more serious difficulty arises in connection with using FSL to describe assembly languages. An assembly language consists of the symbolic representation of a machine order code along with certain high level operators called macro-operations and pseudo-operations. The crucial feature is that an assembly language has a basic 1:1 correspondence with the computer on which it is to run. There is no simple way to capture this essential feature in FSL.

The missing concept here is a formalism for describing the characteristics of a computer. This is one of the most important problems in the theory of computing at the present time and will be discussed further in Section V-B. This same difficulty occurs in trying to describe FSL in FSL. In order to build good translators, one must make a particular implementation of FSL highly dependent on the characteristics of the object machine. One could write the semantics of FSL in FSL, but the result would not be at all indicative of the structure of the language. This is not so surprising when one recalls that FSL was designed to replace assembly languages in describing translators.

The remaining question concerns the quality of translators produced by an FSL system. This is very difficult to evaluate because there are many qualities of a good translator and these are not all mutually compatible. Language designers have always had to evaluate the relative emphasis to be placed on time and storage space at compile time and at run time. In addition, error detection and recovery features are a major consideration.

We have attempted, in the FSL system, to allow the individual language designer to make these choices for himself. All of the translators designed so far have been influenced by the nature of the program load at Carnegie Tech. Since there are a large number of student runs and input-output is on-line, at least half of the computer's time is spent translating programs. For this reason, a translator which produces marvelous code at the expense of compile time is not locally desirable.

The translators for algebraic language produced by the FSL system seem comparable with hand coded translators on the G-20. The compile speeds are equally good, (most of the time is spent in character scanning in any case) and the code produced is locally good though the code does not have interesting global features. In Section V-B we discuss the question of producing highly efficient code using an FSL system.

A major weakness of the current system is the space it occupies at compile time. This arises because all features of the system are present in every translator. This difficulty can be eliminated by using a relocator routine which loads only those features needed for a particular language. For example, the small language translator could be made about 20 per cent smaller by these techniques.

The error detection and recovery features of the system are potentially quite good. An example of an elaborate error scheme for ALGOL 60 using the Production Language may be found in reference [13]. Several debugging aids are also included as a basic part of the FSL system.

The subject of machine independence is one on which we have little information. In the discussion of implementation in Chapter IV we described a technique for using existing translators as part of an FSL system. There is no apparent reason why such a system could not be implemented on any large general purpose machine. However, since there is only one extant implementation of FSL, no more precise claim can be made at this time. These questions on the adequacy of FSL will be considered further in the next section, which deals with areas for future research.

B. Future Research

As mentioned in the preceding section, there are many improvements which could be added to the FSL system. There are several programming constructs, notably linked lists, which have not yet been formalized in the system. A relocator would enable the Basic Compiler to use only required space at translate time. With a relocator comes the ability to add new routines to the repertoire of the Basic Compiler directly in an FSL program.

Another set of additions would be useful for improving the quality of code produced by the system. Although global optimization rules such as the recognition of common subexpressions can be programmed in FSL, we would suggest an alternative course of action. At least on the G-20, much global optimization can be done on the resulting object code. With very little information about the source language (e.g., location of brackets and branch points) one can produce remarkably good code. A routine to perform these operations will be added to the system with a switch making its use optimal. This has the advantage that it will be available to all users of the FSL system, but need not be used in programs not yet debugged.

We also plan to add a complete assembly language to the FSL system. While this is distasteful from an abstract viewpoint, it will enable one to utilize machine dependent features when their use is warranted. This should not interfere with communication between humans because the published version of a translator would be written wholly in FSL with notes about the parts which were recoded in assembly language. This technique is used currently in communicating algorithms written in problem-oriented source languages such as ALGOL or LISP.

Another set of improvements concern the input text character scanner which is part of all languages written in FSL. At the present time the scanner contains several fixed conventions such as which characters can be juxtaposed to form an identifier. One would like a set of declarations in the productions of source language to describe such variable conditions as fixed field scanning as well as those mentioned above.

The major weakness in the system is its inability to describe assembly language and other machine dependent systems. Since the FSL system is equivalent to a Turing machine and hence,"all things are possible", we must clarify what is meant by 'inability'.

If one were given the task of writing an assembler for the G-20 in FSL there are two basic approaches one could take. Since an assembly language is just another computer language, we could write it machine-independent semantics just as we would those for ALGOL. This would have the pleasant property that the assembly language would function on any machine having an FSL implementation. The problem is that on the G-20 the code produced by this assembler would be intolerable. Where a convential assembler is 1:1 with machine code in its basic operations, the FSL assembler would, in essence, be simulating the computer on itself.

There is another way of attacking this problem in FSL. Since we know the internal representation of G-20 commands we could build a table of them using FSL. FSL also contains operations for uniting in, and extracting off, bit patterns so we could build G-20 commands much as a conventional assembler would. Although it might take longer, there is every reason to suspect that the FSL assembler would create good code. With this approach the difficulty is that the FSL semantics does not describe the nature of the language being described and would be absolutely useless on a machine different than the G-20.

The solution to this dilemma requires a formal language capable of expressing the properties of a computer, as FSL does for a computer language. Since there is no clear dividing line between the properties of computers and of computer languages, this additional language might well be an extension of FSL. The difficulties involved in formalizing the properties of computing machines and machine-like languages are immense. Although no solutions exist at this time, there are several efforts in this direction and results can be hoped for in the near future.

An extension to FSL which would allow the process description of computers would do far more than solve the problem of building assembly languages. If one had such a language the model of the compiler-compiler could be extended to include a formal description of the target (object) language. This description could then be processed by a program which would produce generators to be used by the old FSL system. The object language would always be machine-like but the source language could vary in type. If the source language were a problem-oriented language like those discussed in this paper, the compiler-compiler would be the same except that it could produce a variety of machine and assembly codes. Assembly languages could be designed so that they would work efficiently on machines that matched their characteristics. Further, if the source language were also machine-like, the compiler-compiler would produce a simulator of the source machine on a target machine.

It appears that the picture above assumes that once the meta-language is prescribed there will be little difficulty involved in the construction of processors. Our experience with programming in general and FSL in particular indicates that this is largely the case. Perhaps the point is that a sine qua non for an adequate computer language is that it contain an implicit description of its processor. In any event, a formalization of the properties of computers would be a major advance in the theory of programming languages.

The introduction of a semantic meta-language such as FSL raises another set of questions entirely distinct from those considered above. These all deal with the properties of FSL as a formal system. The most interesting question regards the relationship of FSL to various notions of formalized semantics used in mathematical logic. A preliminary investigation of this question left us with no concrete results.

One might also want to use the idea of formal semantics to define a notion of formal translation. Intuitively, one would describe translation as a process which preserves meaning. The many treatments of translation as a purely syntactical process, while very valuable, do not capture this intuitive concept of translation. If there were a fixed semantic meta-language, one could discuss translation as a process conserving semantics in that meta-language. This would leave the problem of determining the equivalence of two statements in the meta-language, but at least it would create a well-defined problem area where before there was none.

Among the questions one might want to ask are the following. Is this program in ALGOL equivalent to that LISP routine? Is language A strictly weaker than (or equivalent to) language B? Can I find a shorter program in another language which will have the same meaning as this one? While all of these questions will all still be undecidable in the formal sense, representation in a fixed meta-language should make particular cases more tractable, i.e., provide representations for special proofs.

We have presented in this paper a number of ideas, some borrowed, some new, about the formalization of computer-oriented languages. The most significant was a semantic meta-language, FSL, which seems to provide new opportunities in several areas of programming research. Besides its use on a compiler-compiler, FSL has proved useful in teaching language design and shows promise of helping to provide insight into the nature of computer-oriented languages.

Whatever the merits of our particular system, some such formalized system will have a marked effect on language design. Picture, if you will, a time when there are standard formalisms for expressing the syntax and semantics of computer languages.

Then suppose a language designer devises a language for expressing a certain class of problems. First of all, in specifying formally its syntax and semantics, he is forced to make his ideas precise. Since the formalisms are translator oriented it will be hard to specify those constructs which are unnatural to implement. Once the language is specified the meta-compiler will automatically produce a translator on which the designer can try his problems. Should the language prove acceptable he could then publish his formal description much as algorithms are now published in the Communications of the ACM. But, this published version is also the complete specification of a translator from his language to any machine which has an implementation of the formal system. All of this does more than present an intriguing picture, it describes a situation which should be realized in the near future.

APPENDICES

Notes on the Appendices

The material contained in these appendices forms an integral part of the thesis. The basis for most of them is one or more machine listings. In all cases these are actual runs of the programs being described.

Appendices A-C comprise a complete description of the subset of ALGOL 60 which we call the small language. The BNF syntax of the small language which is Appendix A is what might be given in a published paper on the small language. The Appendices B and C are a solution to the problem of building a compiler for the small language.

Appendix B contains a run of the production loader on the syntax of the small language. The results of this run are some tightly packed tables which will control the scanning of small language source programs. The notation used in these tables is described in that section.

Appendix C contains a run of the semantic loader on the FSL semantics of the small language. The tables produced there are actually short programs which will be executed by the Basic Compiler. We will give a capsule description of the G-20 machine code at the end of these notes. This description will also be of use in reading Appendix F, which contains the translations of sample programs in the small language.

Appendices D and E describe the semantic meta-language, FSL. The Backus Normal Form syntax constitutes Appendix D while the Production Language Syntax is Appendix E. The tables produced in Appendix E follow the same format as those for the productions of the small language (Appendix B).

In order to fully understand the appendices, one must have some knowledge of G-20 machine code. We will present a brief description of the machine, emphasizing its differences from the better known computers of its class.

The Control Data (neé Bendix) G-20 at Carnegie Tech is a large single address machine. Among its more interesting features are a floating point accumulator and a special operand assembly (OA) register. These are the only hardware registers with which we will be concerned. Although the G-20 has 64 index registers, these are in its 6 μ-second core memory and thus have appreciable access times. We will describe the G-20 command structure as it will appear in Appendices C and F. The format of a command is:

f xxx m ddddd , ii

whre 'f' denotes the interrupt flag (0-3) used by the machine hardware. The symbols 'xxx' denote one of the 3-letter mnemonic opcodes which we will describe below. The 'm' denotes the addressing mode (0-3) and will also be described below. The field marked 'ddddd' stands for the five digit octal address used in a G-20 command and the 'ii' denotes one of the octal 100 index registers (0-77). The internal representation of a command is slightly different than our picture.

Before describing the commands, we must say something about the address structure of the G-20. This is based on the use of the OA register which automatically combines with the address field of every command according to the mode specified in the command. If we represent the address field of a command by A, the index field by I and the contents of OA register as (OA) we attain the following rules for building X, the effective address.

Mode	Effective Address
0	$(OA) + A + (I) = X$
1	$(OA) + (A) + (I) = X$
2	$((OA) + A + (I)) = X$
3	$((OA) + (A) + (I)) = X$

The normal mode for stores and transfer commands is mode 0, while all other commands are normally in mode 2. There are special commands for operating on the OA and, except for these instructions, the OA is set to zero after every command.

In the table of opcodes (Figure 4), (ACC) stands for the accumulator and all the symbols defined above retain their meanings. Notice that for all conditional statements the next command is executed if the

Partial List of G-20 Opcodes

Address Preparation

OCA	$X \rightarrow (OA)$
OCA	$-X \rightarrow (OA)$
OAD	$(ACC) + X \rightarrow (OA)$
OSU	$(ACC) - X \rightarrow (OA)$

Add and Substract

CLA	$X \rightarrow (ACC)$
CLS	$-X \rightarrow (ACC)$
ADD	$(ACC) + X \rightarrow (ACC)$
SUB	$(ACC) - X \rightarrow (ACC)$
ADN	$-(ACC) - X \rightarrow (ACC)$
SUN	$-(ACC) + X \rightarrow (ACC)$
ADA	$(ACC) + X \rightarrow (ACC)$
SUA	$(ACC) - X \rightarrow (ACC)$

Arithmetic Tests

FOM	$X < 0$
FOP	$X > 0$
FLO	$(ACC) < X$
FGO	$(ACC) > X$

Multiply and Divide

MPY	$(ACC) * X \rightarrow (ACC)$
DIV	$(ACC) / X \rightarrow (ACC)$
RDV	$X / (ACC) \rightarrow (ACC)$

Logic Operations

CAL	$X \quad (ACC)$
CCL	$X \quad (ACC)$
ADL	$(ACC) + X \rightarrow (ACC)$
SUL	$(ACC) - X \rightarrow (ACC)$
EXL	$(ACC) \wedge X \rightarrow (ACC)$
UNL	$(ACC) \vee X \rightarrow (ACC)$

Logic Tests

IOZ	$X = 0$
IOZ	$X = 0$
IUO	$(ACC) - X \neq 0$

Store

STL	$(ACC) \rightarrow X$
STD	$(ACC) \rightarrow X$
STI	$(ACC) \rightarrow X$
.STZ	$0 \rightarrow X$

Index Register Codes

LXP	$X \rightarrow I$	
LXM	$-X \rightarrow I$	
ADX	$(I) + X \rightarrow I$	
SUX	$(I) - X \rightarrow I$	
AXT	$(I) + X \rightarrow I$	(=0?)
SXT	$(I) - X \rightarrow I$	(=0?)

Transfer of Control

TRA	$X \rightarrow NC$
TRM	$(NC) \rightarrow X; X + 1 \rightarrow NC$

Figure 4.

condition holds. With this capsule view of the G-20 and the descriptions accompanying the examples, it should be possible to follow the code generated in Appendices C and F. A much more complete set of examples, including a number of source languages, will appear as a separate paper.

Appendix A

Syntax of a Small Language

```
<arithmetic expression> :: =  <term> | ± <term> |
                               <arithmetic expression>  ±  <term>

<term>  :: =  <factor> | <term> */ <factor>

<factor>  :: =  <primary> | <factor> ↑ <primary>

<primary>  :: =  <identifier> | (<arithmetic expression>)

<simple boolean>  :: =  <identifier> | <arithmetic expression>
                        <relation>  <arithmetic expression>

<boolean>  :: =  <simple boolean> | <if clause> <simple boolean>
                        ELSE  <boolean>

<if clause>  :: =  IF <boolean> THEN

<if statement>  :: =  <if clause>  <unconditional>

<assignment>  :: =  <identifier> ← <arithmetic expression> |
                        <identifier> ← <boolean>

<go to statement>  :: =  GO TO <identifier>

<conditional>  :: =  <if statement> | <if statement>  ELSE <statement>

<unconditional>  :: =  <assignment> | <go to statement> | <block>

<declaration>  :: =  <type>  <type list> | <declaration> ; <type>
                        <type list>

<type>  :: =  REAL | BOOLEAN | LABEL

<type list>  :: =  <identifier> | <type list> , <identifier>

<head>  :: =  BEGIN | BEGIN <declaration> | <head> ; <statement>

<block>  :: =  <head>  END

<statement>  :: =  <conditional> | <unconditional> | <empty> |
                        <identifier> : <statement>
```

Notes on Appendix B

The appendix is a machine run of the Production Language syntax of the small language. Besides the productions themselves there are three tables given as input to the Production Loader. The first is a table of reserved identifiers, both those used internally and those which appear in the source code. The second table defines the class names (meta-characters) as discussed in Chapter II. The table of actions contains all those mentioned in Chapter II as well as others used internally by the system.

As we have mentioned, the tables built by the Production Loader are tightly packed and thus difficult to read. The small table at 37715 to 40011 contains initializing information for the Basic Compiler. The two tables (other stuff and LABELS) before the production table contain debugging information which will not concern us here.

To read the production table we must understand the internal numbering system for symbols. Reserved symbols are given octal integers starting at 200 as internal names. After the last number assigned to a reserved symbol (261 for the small language), the source code identifiers are numbered sequentially.

The production table consists of two types of words, head cells and operands. Consider the first entry (62245) in the production table.

```
0  105  02  10000
```

The '105' marks this as the head cell of a production and the '02' gives the relative address of the next head cell. The '10000' is the relative address of the interpretation table entry corresponding to this production. We will discuss the interpretation table below.

The next cell contains '252' in the low order positions. This is the octal integer which corresponds to 'BEGIN'. A word of all zeros in the production table corresponds to a ' Ø ' in a production.

The interpretation table is easier to follow. The integer in the high order position represents one of the actions in the Action Table. These are numbered sequentially starting with '1' for EXEC. The parameter to the action is contained in the low order bits of the same word. These tables are interpreted by the Basic Compiler in recognizing source language text.

Appendix B

Productions for the Small Language

```
*        SYMBOLS
*         12 INTERNAL SYMBOLS
                           I
                           P
                           F
                           T
                           E
                           SBE
                           BE
                           ICL
                           UN
                           S
                           HEAD
                           |→
     +                     +
     -                     -
     *                     *
     /                     /
     =                     =
     ∨                     ∨
     ≠                     ≠
     ∧                     ∧
     <                     <
     >                     >
     ¬<                    ¬<
     ¬>                    ¬>
     ¬                     ¬
     ↑                     ↑
     ↓                     ↓
     .                     .
     ,                     ,
     ;                     ;
     :                     :
     ←                     ←
     →                     →
     $                     $
     (                     (
     [                     [
     ]                     ]
     )                     )
     REAL                  REAL
     BOOLEAN               BOOL
     LABEL                 LABL
     BEGIN                 BEGN
     END                   END
     GOTO                  GO
     IF                    IF
     THEN                  THEN
     ELSE                  ELSE
     TRUE                  TRUE
     FALSE                 FALS
*        METACHARACTERS
```

```
M <UP> + - * / ↑
M <IP> REAL BOOL LABL
M <RL> = ≠ < > ¬< ¬>
M <PM> + -
M <IO> * /
*         ACTIONS

    EXEC
    NSTK
    STAK
    VALU
    SUBR
    SCAN
    NEXT
    GET
    BOOK
    RETURN
    ERROR
    HALT
    CON
    NUM
    FOUT
    STRIN
*         PRODUCTIONS
37715   00000000074  00053117163  00003754224  00001020101  00003720323  00000000523  00001336065  00000016307
37725   00017232775  00125776240  20000034000  01177202242  00003402170  00000000073  00000000072  00000000071
37735   00000000070  00000000065  00000000035  00000000034  00000000076  00000000067  00000000037  00000000053
37745   00000000074  00000000075  00000000036  00000000036  00000000036  00000000066  00000000064  00000000063
37755   00000000062  00000000061  00000000060  00000000057  00000000056  00000000055  00000000054  30000000000
37765   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37775   30000000000  30000000000  30000000000  00000000261  30000000000  02000000046  00000000032  00000000014
40005   30000000000  02000000062  00000000213  30000000000  30000000000
...
```

```
S0                      BEGN  |                       |  EXEC 1     *D1
                        <SG>  |                       |  ERROR 0    Q1
D1                      <TP>  |                       |  SCAN       *D2
                  BEGN  END   | →               S     |             *S1
                  BEGN  ;     | →               BEGN  |             *D1
            BEGN  |→    <SG>  | → HEAD ;        <SG>  |  EXEC 2     S1
                  BEGN  <SG>  | → HEAD ;        <SG>  |  EXEC 2     S1
D2          REAL  I     <SG>  |                       |  EXEC 4     D3
            BOOL  I     <SG>  |                       |  EXEC 5     D3
            LABL  I     <SG>  |                       |  EXEC 30    D3
D3          <TP>  I     ,     | →               <TP>  |  SCAN       *D2
       |→   <TP>  I     ;     | →               |→    |             *D1
            <TP>  I     ;     | →               |→    |             *D1
                        <SG>  |                       |  ERROR 1    Q1
S1                      BEGN  |                       |             *D1
                        IF    |                       |             *B1
                        GO    |                       |             *G1
                        ;     | →         S     ;     |             S9
                        END   |                       |             S9
                        I     |                       |             *S2
S2                I     :     | →                     |  EXEC 26    *S1
                  I     ←     |                       |             *EX1
                        <SG>  |                       |  ERROR 2    Q1
I1                ←     ICL   |                       |             *B1
                  IF    ICL   |                       |             *B1
            SBE   ELSE  ICL   |                       |             *B1
                        ICL   |                       |  EXEC 3     *S1
                        <SG>  |                       |  ERROR 4    Q1
UN1         ICL   UN    <SG>  |                       |             C1
                  UN    <SG>  | →         S     <SG>  |             S9
                        <SG>  |                       |  ERROR 5    Q1
C1          ICL   UN    ELSE  |                       |  EXEC 6     *S1
            ICL   UN    <SG>  | →         S     <SG>  |  EXEC 7     S9
                        <SG>  |                       |  ERROR 6    Q1
P1                      I     | →               P     |  EXEC 9     *F1
                        (     |                       |             *P1
                        +     | →                     |             *P1
                        -     |                       |             *P1
                        <SG>  |                       |  ERROR 7    Q1
F1     F    ↑     P     <SG>  | →         F     <SG>  |  EXEC 28    F2
                  P     <SG>  | →         F     <SG>  |             F2
F2                F     ↑     |                       |             *P1
T1     T    *     F     <SG>  | →         T     <SG>  |  EXEC 10    T2
       T    /     F     <SG>  | →         T     <SG>  |  EXEC 11    T2
                  F     <SG>  | →         T     <SG>  |             T2
T2                T     <TD>  |                       |             *P1
E1     E    +     T     <SG>  | →         E     <SG>  |  EXEC 12    E2
       E    -     T     <SG>  | →         E     <SG>  |  EXEC 13    E2
            -     T     <SG>  | →         E     <SG>  |  EXEC 14    E2
                  T     <SG>  | →         E     <SG>  |             E2
E2                E     <PM>  |                       |             *P1
            (     E     )     | →               P     |  EXEC 15    *F1
                  E     <RL>  |                       |             *P1
       I    ←     E     <SG>  | →         UN    <SG>  |  EXEC 16    UN1
       E    =     E     <SG>  | →         SBE   <SG>  |  EXEC 17    B2
```

```
                E       <       E       <SG>   | →    SBE     <SG>   |    EXEC 18      B2
                E       >       E       <SG>   | →    SBE     <SG>   |    EXEC 19      B2
                E       <RL>    E       <SG>   | →    SBE     <SG>   |    EXEC 17      B2
                                        <SG>   |                     |    ERROR 8      Q1
B1                                      IF     |                     |                 *B1
                                        +      | →                   |                 *P1
                                        -      |                     |                 *P1
                                        (      |                     |                 *P1
B4                              I       <OP>   | →    P       <OP>   |    EXEC 8       F1
                                I       <RL>   | →    E       <RL>   |    EXEC 8       *P1
                                I       <SG>   | →    SBE     <SG>   |    EXEC 20      B2
                                        I      |                     |                 *B4
B2                              SBE     ELSE   |                     |                 *B1
                                SBE     <SG>   | →    BE      <SG>   |                 B3
B3                      IF      BE      THEN   | →            ICL    |    EXEC 21      I1
        ICL     SBE     ELSE    BE      <SG>   | →    BE      <SG>   |    EXEC 22      B3
                I       ←       BE      <SG>   | →    UN      <SG>   |    EXEC 23      UN1
EX1                                     I      |                     |                 *EX2
                                        IF     |                     |                 *B1
                                        +      | →                   |                 *P1
                                        -      |                     |                 *P1
                                        (      |                     |                 *P1
EX2                             I       <OP>   | →    P       <OP>   |    EXEC 8       F1
                                I       <RL>   | →    E       <RL>   |    EXEC 8       *P1
                I       ←       I       <SG>   | →    UN      <SG>   |    EXEC 24      UN1
                                        <SG>   |                     |    ERROR 8      Q1
G1                              GO      I      | →            UN     |    EXEC 25      *UN1
                                        <SG>   |                     |    ERROR 9      Q1
S9      ICL     UN      ELSE    S       <SG>   | →    S       <SG>   |    EXEC 27      S9
        ICL     UN      ELSE    UN      <SG>   | →    S       <SG>   |    EXEC 27      S9
                HEAD    ;       S       ;      | →    HEAD    ;      |                 *S1
                HEAD    ;       S       END    | →            UN     |    EXEC 29      ND1
ND1                             |→      UN     | →            |→     |    EXEC 31      Q1
                                        <SG>   |                     |                 *UN1
Q1                                      <SG>   |                     |    HALT         Q1
*               END
```

```
OTHER STUFF
I 1          4
I 2          0
I 3          0
I 4          1
I 5          0
I 6         14
I 7         61
I 8         67
I 9          0
I10         56
I11         67
I12         12
I13         12
I14          5
I15          0
I16         26
```

```
I17          2
I18        293
I19   •      0
I20         28
I21      16333
J 0        287
J 1          0
J 2          1
J 3         61
J 4         67
J 5          7
J 6         51
J 7         12

            LABEL TABLE

         LABEL NAME    VALUE
   1        S0             0
   2        D1             4
   3        Q1           285
   4        D2            19
   5        S1            46
   6        D3            31
   7        B1           190
   8        G1           253
   9        S9           258
  10        S2            58
  11        EX1          230
  12        I1            66
  13        UN1           80
  14        C1            89
  15        P1            99
  16        F1           109
  17        F2           117
  18        T1           120
  19        T2           133
  20        E1           136
  21        E2           153
  22        B2           209
  23        B4           198
  24        B3           215
  25        EX2          240
  26        ND1          280
  27                       1

            PRODUCTION TABLE
62245    01050210000   00000000252   01050210003   00000000000   01050210005   01050300006   01050310010   00000000253
62255    00000000252   01050310014   00000000235   00000000252   01050410017   00000000000   00000000213   00000000252
62265    01050310025   00000000000   00000000252   01050410033   00000000000   00000000200   00000000246   01050410035
62275    00000000000   00000000200   00000000250   01050410037   00000000000   00000000200   00000000251   01050410041
62305    00000000234   00000000200   01050300006   01050510045   00000000235   00000000200   01050300006   00000000213
62315    01050410059   00000000235   00000000200   01050300006   01050210054   00000000000   01050210056   00000000252
62325    01050210060   00000000255   01050210062   00000000254   01050210064   00000000235   01050210070   00000000253
62335    01050210071   00000000200   01050310073   00000000236   00000000200   01050310077   00000000237   00000000200
```

```
62345   01050210101  00000000000  01050310103  00000000207  00000000237  01050310105  00000000207  00000000255
62355   01050410107  00000000207  00000000257  00000000205  01050210111  00000000207  01050210114  00000000000
62365   01050410116  00000000000  00000000210  00000000207  01050310117  00000000000  00000000210  01050210123
62375   00000000000  01050410125  00000000257  00000000210  00000000207  01050410130  00000000000  00000000210
62405   00000000207  01050210135  00000000000  01050210137  00000000200  01050210144  00000000242  01050210146
62415   00000000214  01050210151  00000000215  01050210153  00000000000  01050510155  00000000000  00000000201
62425   00000000231  00000000202  01050310161  00000000000  00000000201  01050310165  00000000231  00000000202
62435   01050510167  00000000000  00000000202  00000000216  00000000203  01050510173  00000000000  00000000202
62445   00000000217  00000000203  01050310177  00000000000  00000000202  01050310203  01050200021  00000000203
62455   01050510205  00000000000  00000000203  00000000214  00000000204  01050510211  00000000000  00000000203
62465   00000000215  00000000204  01050410215  00000000000  00000000203  00000000215  01050310222  00000000000
62475   00000000203  01050310226  01050200017  00000000204  01050410230  00000000245  00000000204  00000000242
62505   01050310235  01050600011  00000000204  01050510237  00000000000  00000000204  00000000237  00000000200
62515   01050510244  00000000000  00000000204  00000000220  00000000204  01050510251  00000000000  00000000204
62525   00000000224  00000000204  01050510256  00000000000  00000000204  00000000225  00000000204  01050510263
62535   00000000000  00000000204  01050600011  00000000204  01050210270  00000000000  01050210272  00000000255
62545   01050210274  00000000214  01050210277  00000000215  01050210301  00000000242  01050310303  01050500001
62555   00000000200  01050310310  01050600011  00000000200  01050310316  00000000000  00000000200  01050210323
62565   00000000200  01050310325  00000000257  00000000205  01050310327  00000000000  00000000205  01050410333
62575   00000000256  00000000206  00000000255  01050610337  00000000000  00000000206  00000000257  00000000205
62605   00000000207  01050510344  00000000000  00000000206  00000000237  00000000200  01050210351  00000000200
62615   01050210353  00000000255  01050210355  00000000214  01050210360  00000000215  01050210362  00000000242
62625   01050310364  01050500001  00000000200  01050310371  01050600011  00000000200  01050510377  00000000000
62635   00000000200  00000000237  00000000200  01050210404  00000000000  01050310406  00000000200  00000000254
62645   01050210413  00000000000  01050610415  00000000000  00000000211  00000000257  00000000210  00000000207
62655   01050610422  00000000000  00000000210  00000000257  00000000210  00000000207  01050510427  00000000235
62665   00000000211  00000000235  00000000212  01050510432  00000000253  00000000211  00000000235  00000000212
62675   01050310436  00000000210  00000000213  01050210441  00000000000  01050210443  00000000000  30000000000

          AUXILIARY PRODUCTION TABLE
65202   00000000000  00000000210  00000000213  00000000253  00000000210  00000000235  00000000000  30000000000
65212   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
65222   30000000000  30000000000  30000000000  30000000000

          INTERPRETATION TABLE
65227   00010000001  00060000001  00070000004  00130000000  00070000435  00060000000  00060000001  00070000023
65237   00020000002  00030000211  00060000001  00070000056  00020000001  00060000001  00070000004  00020000003
65247   00030000212  00030000235  00030000000  00010000002  00070000056  00020000002  00030000212  00030000235
65257   00030000000  00010000002  00070000056  00010000004  00070000037  00010000005  00070000037  00010000036
65267   00070000037  00020000002  00060000000  00060000001  00070000023  00020000003  00060000001  00070000004
65277   00020000003  00030000213  00060000001  00070000004  00130000001  00070000435  00060000001  00070000004
65307   00060000001  00070000276  00060000001  00070000375  00020000001  00030000211  00030000000  00070000402
65317   00070000402  00060000001  00070000072  00020000002  00010000032  00060000001  00070000056  00060000001
65327   00070000346  00130000002  00070000435  00060000001  00070000276  00060000001  00070000276  00060000001
65337   00070000276  00010000003  00060000001  00070000056  00130000004  00070000435  00070000131  00020000002
65347   00030000211  00030000000  00070000402  00130000005  00070000435  00010000006  00060000001  00070000056
65357   00020000003  00030000211  00030000000  00010000007  00070000402  00130000006  00070000435  00020000001
65367   00030000201  00010000011  00060000001  00070000155  00060000001  00070000143  00020000001  00060000001
65377   00070000143  00060000001  00070000143  00130000007  00070000435  00020000003  00030000000  00010000034
65407   00070000165  00020000002  00030000202  00030000000  00070000165  00060000001  00070000143  00020000003
65417   00030000000  00010000012  00070000205  00020000003  00030000000  00010000013  00070000205  00020000002
65427   00030000203  00030000000  00070000205  00060000001  00070000143  00020000003  00030000000  00010000014
65437   00070000231  00020000003  00030000000  00010000015  00070000231  00020000003  00030000204  00030000000
65447   00010000016  00070000231  00020000002  00030000204  00030000000  00070000231  00060000001  00070000143
65457   00020000003  00030000201  00010000017  00060000001  00070000155  00060000001  00070000143  00020000004
```

```
65467   00030000210  00030000000  00010000020  00070000120  00020000004  00030000205  00030000000  00010000021
65477   00070000321  00020000004  00030000205  00030000000  00010000022  00070000321  00020000004  00030000205
65507   00030000000  00010000023  00070000321  00020000004  00030000205  00030000000  00010000021  00070000321
65517   00130000010  00070000435  00060000001  00070000276  00020000001  00060000001  00070000143  00060000001
65527   00070000143  00060000001  00070000143  00020000002  00030000201  00030000000  00010000010  00070000155
65537   00020000002  00030000204  00030000000  00010000010  00060000001  00070000143  00020000002  00030000205
65547   00030000000  00010000024  00070000321  00060000001  00070000306  00060000001  00070000276  00020000002
65557   00030000206  00030000000  00070000327  00020000003  00030000207  00010000025  00070000102  00020000005
65567   00030000001  00030000000  00010000026  00070000327  00020000004  00030000210  00030000000  00010000027
65577   00070000120  00060000001  00070000360  00060000001  00070000276  00020000001  00060000001  00070000143
65607   00060000001  00070000143  00060000001  00070000143  00020000002  00030000201  00030000000  00010000010
65617   00070000155  00020000002  00030000204  00030000000  00010000010  00060000001  00070000143  00020000004
65627   00030000210  00030000000  00010000030  00070000120  00130000010  00070000435  00020000002  00030000210
65637   00010000031  00060000001  00070000120  00130000011  00070000435  00020000005  00030000001  00030000000
65647   00010000033  00070000402  00020000005  00030000211  00030000000  00010000033  00070000402  00020000002
65657   00060000001  00070000056  00020000004  00030000210  00010000035  00070000430  00020000001  00010000037
65667   00070000435  00060000001  00070000120  00140000000  00070000435
•        TAPE 210
              RECORD TYPE                  NUMBER OF RECORDS   STARTING RECORD

          SYMBOL TABLE                             1                  21 •+01
          HIERARCHY TABLE                          1                  21 •+01
          PRODUCTION TABLE                         1                  22 •+01
          METACHARACTER LISTS                      1                  22 •+01

        TIME USED:  00:02:43     PAGES USED:   8            19:14:09
```

Notes on Appendix C

This is a complete run of the semantics for the small language. All of the locations are in octal form and the meaning of the mnemonic opcodes is given at the beginning of the appendices. The semantic tables start at 65600 and extend to 66650. The table of addresses starting at 37000 is called the switching table. Each entry in this table is the first location of the code for a semantic routine. For example, the code for 12↓ (octal 14) starts at 66101 as described in cell 37014. The switching table is used by the compiler in executing semantic routines.

As an example we will consider the code generated for

12↓ CODE(VALUE2 ← LEFT4 + LEFT2) ↓

The first command increments a pointer because we are entering code brackets. The next four commands put LEFT4 (63337) and LEFT2 (63335) into the parameter region. Then the generator for '+' is called by 'TRM 0 63405'. The next two commands set up and call the processor for 'VALUE2' which will adjust the compile time stack and put an accumulator symbol in RIGHT2. Finally, the semantic routine returns control to the basic compiler at 62110.

Tables and other storage for the translator start at 45777 and go down in memory. Addresses between 62000 and 65000 refer to routines in the basic compiler. Locations near 14400 are used for constants and any address below 10000 is in the monitor, except for the index registers 0-77.

```
≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠;

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                                                      00:00:03




CO                                       APPENDIX C
CO                 FORMAL SEMANTICS OF THE SMALL LANGUAGE

SN       DUMP

   BEGIN TABLE SYMB[200,4] ; CELL LEV,T0,T1,T2,T3,T4,T5; STACK STR,SYM;
   TITLE REAL, BOOL, LABE; DATA LOGIC, INTEGER, SINGLE, DOUBLE;

   0↓  T3 ← TEMPLOC ↓

   1↓ LEV ← 0; STR ← STORLOC; SYM ← LOC[SYMB] ↓

   2↓ LEV ≠0 → PUSH[STR,STORLOC]; PUSH [SYM, LOC[SYMB]]$    ;
       TALLY[LEV] ↓

   3↓ PUSH[FLAD1,0]; CODE( ¬LEFT1 → JUMP[FLAD1]$) ↓


   4↓ T0← STORLOC; SET[T0,DOUBLE]; ENTER[ SYMB;LEFT2,T0,REAL,LEV];
      STORLOC ← STORLOC+2 ↓

   5↓ ENTER[SYMB;LEFT2,STORLOC,BOOL ,LEV];TALLY[STORLOC] ↓

   6↓ PUSH[FLAD2,0]; CODE( JUMP[FLAD2]); ASSIGN[FLAD1]↓

   /↓ ASSIGN[FLAD1]↓

   8↓ CONST[LEFT2]→ RIGHT2← LEFT2 :
      SYMB[LEFT2,,$,]= REAL→ RIGHT2← SYMB[LEFT2,$,,]:FAULT 1$$ ↓

   9↓ CONST[LEFT1] → RIGHT1 ← LEFT1 :
      SYMB[LEFT1,,$,]= REAL→ RIGHT1← SYMB[LEFT1,$,,]:FAULT 1$$ ↓

   10↓ CODE(VALUE2←LEFT4*LEFT2)↓

   11↓ CODE(VALUE2←LEFT4/LEFT2)↓

   12↓ CODE(VALUE2←LEFT4+LEFT2)↓

   13↓ CODE(VALUE2←LEFT4-LEFT2)↓

   14↓ CODE(VALUE2←-LEFT2)↓
```

```
15↓ RIGHT1←LEFT2↓

16↓ SYMB[LEFT4,,$,]=REAL→ COMT 2← SYMB[LEFT4,$,,];
    CODE(COMT 2← LEFT2) ; TEMPLOC ← T3 : FAULT 3$ ↓

17↓ CODE(VALUE2←LEFT4=LEFT2)↓

18↓ CODE(VALUE2←LEFT4<LEFT2)↓

19↓ CODE(VALUE2←LEFT4>LEFT2)↓

20↓CONST[LEFT2]→ RIGHT2← LEFT2 :
    SYMB[LEFT2,,$,]=BOOL→RIGHT2←SYMB[LEFT2,$,,];
  SET[RIGHT2,LOGIC] ; TEMPLOC ← T3 : FAULT 3$$↓

21↓ RIGHT1 ← LEFT2 ↓

22↓ CODE( LEFT5→ TEMPLOC← LEFT4:  TEMPLOC← LEFT2$) ;
    RIGHT2← TEMPLOC; SET[RIGHT2,LOGIC] ;
   TALLY[TEMPLOC] ↓

23↓ SYMB[LEFT4,,$,]=BOOL→ COMT 2← SYMB[LEFT4,$,,];
    CODE( COMT 2← LEFT2): FAULT 4$ ↓

24↓ COMT 4← SYMB[LEFT4,$,,];
   CONST[LEFT2] → COMT 2← LEFT2:
    SYMB[LEFT2,,$,]=SYMB[LEFT4,,$,] → COMT 2← SYMB[LEFT2,$,,]:
     FAULT 5 $ $; TEMPLOC ← T3;
   CODE( COMT 4← COMT 2) ↓

25↓ SYMB[LEFT1,,$,] ≠ LABE → FAULT 6:
    COMT 2← LOC[SYMB[LEFT1,$,,]];
   COMT 3← <COMT 2>; SYMB[LEFT1,,,$] ≠0 → CODE( JUMP[COMT 3]) :
   CODE( JUMP[CHAIN[ COMT 2] ]) $$ ↓

26↓ SYMB[LEFT2,,$,] ≠ LABE → FAULT 6:
        SYMB[0,,,$] ` 1 ;
   ASSIGN[LOC [ SYMB[ LEFT2,$,,]]] $↓

27↓ ASSIGN[FLAD2] ↓

28↓ CODE( VALUE2 ← LEFT4 ↑ LEFT2) ↓

29↓ MINUS[LEV]; POP[STR,STORLOC]; POP[SYM,LOC[SYMB]]  ↓

30↓ ENTER[SYMB;LEFT2,0,LABE, 0'] ↓

31↓ CODE( STOP) ↓
```

```
          ENDJ
65600     0 CLA 0 00004,00     0 STI 0 45775,00     0 CLA 0 45774,00     0 STI 0 45777,00     0 CLA 0 00310,00
65605     0 STI 0 45776,00     0 LXP 0 44161,40     0 LXP 0 44015,41     0 CLA 0 00370,00     0 STL 0 44014,00
65612     0 CLA 0 00371,00     0 STL 0 44013,00     0 CLA 0 00372,00     0 STL 0 44012,00     0 CLA 2 00076,00
65617     0 STL 0 44327,00     0 TRA 0 17020,00     0 CLA 0 00000,00     0 STL 0 44333,00     0 CLA 2 00071,00
65624     0 STL 2 00040,00     0 CAL 2 45777,00     0 SIL 2 00041,00     0 TRA 0 62110,00     0 CAL 2 44333,00
65631     0 FUO 0 00000,00     0 TRA 0 65634,00     0 TRA 0 65643,00     0 LXM 0 00001,74     0 ADX 0 00001,40
65636     0 CLA 2 00071,00     0 STL 2 00040,00     0 ADX 0 00001,41     0 CAL 2 45777,00     0 STL 2 00041,00
65643     0 CAL 2 44333,00     0 ADD 0 00001,00     0 STL 0 44333,00     0 TRA 0 62110,00     0 ADX 0 00001,53
65650     0 CLA 0 00000,00     0 STL 2 00053,00     0 CAL 2 63334,00     0 STL 0 63347,00     0 TRM 0 63516,00
65655     0 CAL 2 63351,00     0 STL 0 63346,00     0 TRM 0 63664,00     0 LXM 0 00001,74     0 CAL 0 00053,00
65662     0 UNL 2 63251,00     0 STL 0 63346,00     0 TRM 0 64057,00     0 OCA 2 63365,77     0 CAL 2 00000,00
65667     0 UNL 2 00070,00     0 STL 2 63365,77     0 SUX 0 00001,77     0 LXM 0 00001,74     0 TRA 0 62110,00
656/4     0 CLA 2 00071,00     0 STL 0 44332,00     0 CAL 2 44332,00     0 UNL 2 63275,00     0 UNL 2 63313,00
65701     0 STL 0 44332,00     0 CAL 2 63335,00     0 STL 0 47022,00     0 CAL 2 44332,00     0 STL 0 47023,00
65706     0 CAL 2 44014,00     0 STL 0 47024,00     0 CAL 2 44333,00     0 STL 0 47025,00     0 CLA 0 45777,00
65713     0 TRM 0 64626,00     0 CLA 2 00071,00     0 ADD 0 00002,00     0 STI 0 00071,00     0 TRA 0 62110,00
65720     0 CAL 2 63335,00     0 STL 0 47022,00     0 CAL 2 00071,00     0 STL 0 47023,00     0 CAL 2 44013,00
65725     0 STL 0 47024,00     0 CAL 2 44333,00     0 STL 0 47025,00     0 CLA 0 45777,00     0 TRM 0 64626,00
65732     0 ADX 0 00001,71     0 TRA 0 62110,00     0 ADX 0 00001,54     0 CLA 0 00000,00     0 STL 2 00054,00
65737     0 CAL 0 00054,00     0 UNL 2 63251,00     0 STL 0 63346,00     0 TRM 0 64057,00     0 CAL 0 00053,00
65744     0 UNL 2 63251,00     0 TRM 0 64134,00     0 TRA 0 62110,00     0 CAL 0 00053,00     0 UNL 2 63251,00
65751     0 TRM 0 64134,00     0 TRA 0 62110,00     0 CAL 2 63335,00     0 IEZ 2 63225,00     0 OCS 0 00001,00
65756     0 CAL 2 14377,00     0 IUO 2 14377,00     0 TRA 0 65765,00     0 LXM 0 00001,74     0 CAL 2 63335,00
65763     0 STL 0 63342,00     0 TRA 0 66013,00     0 LXM 0 00001,74     0 LXP 0 00002,52     0 CAL 2 63335,00
657/0     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 FUO 2 44014,00
657/5     0 TRA 0 66007,00     0 LXM 0 00001,74     0 LXP 0 00001,52     0 CAL 2 63335,00     0 STI 0 47034,00
66002     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 STL 0 63342,00     0 TRA 0 66012,00
66007     0 LXM 0 00001,74     0 CLA 0 00001,00     0 TRM 0 64161,00     0 LXM 0 00001,74     0 LXM 0 00001,74
66014     0 TRA 0 62110,00     0 CAL 2 63334,00     0 IEZ 2 63225,00     0 OCS 0 00001,00     0 CAL 2 14377,00
66021     0 IUO 2 14377,00     0 TRA 0 66027,00     0 LXM 0 00001,74     0 CAL 2 63334,00     0 STL 0 63341,00
66026     0 TRA 0 66055,00     0 LXM 0 00001,74     0 LXP 0 00002,52     0 CAL 2 63334,00     0 STI 0 47034,00
66033     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 FUO 2 44014,00     0 TRA 0 66051,00
66040     0 LXM 0 00001,74     0 LXP 0 00001,52     0 CAL 2 63334,00     0 STI 0 47034,00     0 CLA 0 45777,00
66045     0 TRM 0 64570,00     0 CAL 3 47034,00     0 STL 0 63341,00     0 TRA 0 66054,00     0 LXM 0 00001,74
66052     0 CLA 0 00001,00     0 TRM 0 64161,00     0 LXM 0 00001,74     0 LXM 0 00001,74     0 TRA 0 62110,00
66057     0 ADX 0 00001,74     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00
66064     0 TRM 0 63455,00     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00     0 ADX 0 00001,74
660/1     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 63461,00
660/6     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00     0 ADX 0 00001,74     0 CAL 2 63337,00
66103     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 63405,00     0 LXP 0 00001,52
66110     0 TRM 0 62472,00     0 TRA 0 62110,00     0 ADX 0 00001,74     0 CAL 2 63337,00     0 STL 0 63346,00
66115     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 63411,00     0 LXP 0 00001,52     0 TRM 0 62472,00
66122     0 TRA 0 62110,00     0 CAL 2 63335,00     0 SIL 0 63347,00     0 TRM 0 63516,00     0 LXP 0 00001,52
66127     0 TRM 0 62472,00     0 TRA 0 62110,00     0 CAL 2 63335,00     0 STL 0 63341,00     0 TRA 0 62110,00
66134     0 LXP 0 00002,52     0 CAL 2 63337,00     0 SII 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00
66141     0 CAL 3 47034,00     0 FUO 2 44014,00     0 TRA 0 66166,00     0 LXM 0 00001,74     0 LXP 0 00001,52
66146     0 CAL 2 63337,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00
66153     0 STL 0 46465,00     0 ADX 0 00001,74     0 CAL 2 46465,00     0 STL 0 63346,00     0 CAL 2 63335,00
66160     0 STL 0 63347,00     0 TRM 0 63762,00     0 LXM 0 00001,74     0 CAL 2 44327,00     0 STI 0 00076,00
66165     0 TRA 0 66171,00     0 LXM 0 00001,74     0 CLA 0 00003,00     0 TRM 0 64161,00     0 LXM 0 00001,74
661/2     0 TRA 0 62110,00     0 ADX 0 00001,74     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00
661/7     0 STL 0 63347,00     0 TRM 0 63527,00     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00
66204     0 ADX 0 00001,74     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00
66211     0 TRM 0 63537,00     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00     0 ADX 0 00001,74
```

```
66216     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 63543,00
66223     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00     0 CAL 2 63335,00     0 IEZ 2 63225,00
66230     0 OCS 0 00001,00     0 CAL 2 14377,00     0 IUO 2 14377,00     0 TRA 0 66240,00     0 LXM 0 00001,74
66235     0 CAL 2 63335,00     0 STL 0 63342,00     0 TRA 0 66274,00     0 LXM 0 00001,74     0 LXP 0 00002,52
66242     0 CAL 2 63335,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00
66247     0 FUO 2 44013,00     0 TRA 0 66270,00     0 LXM 0 00001,74     0 LXP 0 00001,52     0 CAL 2 63335,00
66254     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 STL 0 63342,00
66261     0 CAL 2 63342,00     0 UNL 2 63272,00     0 UNL 2 63313,00     0 STL 0 63342,00     0 CAL 2 44327,00
66266     0 STI 0 00076,00     0 TRA 0 66273,00     0 LXM 0 00001,74     0 CLA 0 00003,00     0 TRM 0 64161,00
66273     0 LXM 0 00001,74     0 LXM 0 00001,74     0 TRA 0 62110,00     0 CAL 2 63335,00     0 STL 0 63341,00
66300     0 TRA 0 62110,00     0 CAL 2 63340,00     0 STL 0 63346,00     0 TRM 0 63664,00     0 LXM 0 00001,74
66305     0 ADX 0 00001,74     0 CAL 2 00076,00     0 STL 0 63346,00     0 CAL 2 63337,00     0 STL 0 63347,00
66312     0 TRM 0 63762,00     0 LXM 0 00001,74     0 TRM 0 63731,00     0 LXM 0 00001,74     0 ADX 0 00001,74
66317     0 CAL 2 00076,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 63762,00
66324     0 LXM 0 00001,74     0 OCA 2 63365,77     0 CAL 2 00000,00     0 UNL 2 00070,00     0 STL 2 63365,77
66331     0 SUX 0 00001,77     0 LXM 0 00001,74     0 CLA 2 00076,00     0 STL 0 63342,00     0 CAL 2 63342,00
66336     0 UNL 2 63272,00     0 UNL 2 63313,00     0 STL 0 63342,00     0 ADX 0 00001,76     0 TRA 0 62110,00
66343     0 LXP 0 00002,52     0 CAL 2 63337,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00
66350     0 CAL 3 47034,00     0 FUO 2 44013,00     0 TRA 0 66373,00     0 LXM 0 00001,74     0 LXP 0 00001,52
66355     0 CAL 2 63337,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00
66362     0 STL 0 46465,00     0 ADX 0 00001,74     0 CAL 2 46465,00     0 STL 0 63346,00     0 CAL 2 63335,00
66367     0 STL 0 63347,00     0 TRM 0 63762,00     0 LXM 0 00001,74     0 TRA 0 66376,00     0 LXM 0 00001,74
66374     0 CLA 0 00004,00     0 TRM 0 64161,00     0 LXM 0 00001,74     0 TRA 0 62110,00     0 LXP 0 00001,52
66401     0 CAL 2 63337,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00
66406     0 STL 0 46467,00     0 CAL 2 63335,00     0 IEZ 2 63225,00     0 OCS 0 00001,00     0 CAL 2 14377,00
66413     0 IUO 2 14377,00     0 TRA 0 66421,00     0 LXM 0 00001,74     0 CAL 2 63335,00     0 STL 0 46465,00
66420     0 TRA 0 66454,00     0 LXM 0 00001,74     0 LXP 0 00002,52     0 CAL 2 63335,00     0 STI 0 47034,00
66425     0 CLA 0 45777,00     0 TRM 0 64570,00     0 LXP 0 00002,52     0 CAL 2 63337,00     0 STI 0 47034,00
66432     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 FUO 3 47034,00     0 TRA 0 66450,00
66437     0 LXM 0 00001,74     0 LXP 0 00001,52     0 CAL 2 63335,00     0 STI 0 47034,00     0 CLA 0 45777,00
66444     0 TRM 0 64570,00     0 CAL 3 47034,00     0 STL 0 46465,00     0 TRA 0 66453,00     0 LXM 0 00001,74
66451     0 CLA 0 00005,00     0 TRM 0 64161,00     0 LXM 0 00001,74     0 LXM 0 00001,74     0 CAL 2 44327,00
66456     0 STI 0 00076,00     0 ADX 0 00001,74     0 CAL 2 46467,00     0 STL 0 63346,00     0 CAL 2 46465,00
66463     0 STL 0 63347,00     0 TRM 0 63762,00     0 LXM 0 00001,74     0 TRA 0 62110,00     0 LXP 0 00002,52
66470     0 CAL 2 63334,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00
66475     0 FUO 2 44012,00     0 TRA 0 66500,00     0 TRA 0 66504,00     0 LXM 0 00001,74     0 CLA 0 00006,00
66502     0 TRM 0 64161,00     0 TRA 0 66543,00     0 LXM 0 00001,74     0 LXP 0 00001,52     0 CAL 2 63334,00
66507     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 2 47034,00     0 STL 0 46465,00
66514     0 CAL 3 46465,00     0 STL 0 46466,00     0 LXP 0 00003,52     0 CAL 2 63334,00     0 STI 0 47034,00
66521     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CAL 3 47034,00     0 FUO 0 00000,00     0 TRA 0 66527,00
66526     0 TRA 0 66534,00     0 LXM 0 00001,74     0 CAL 2 46466,00     0 STL 0 63346,00     0 TRM 0 64057,00
66533     0 TRA 0 66542,00     0 LXM 0 00001,74     0 CAL 2 46465,00     0 TRM 0 64126,00     0 CAL 2 63351,00
66540     0 STL 0 63346,00     0 TRM 0 64057,00     0 LXM 0 00001,74     0 LXM 0 00001,74     0 TRA 0 62110,00
66545     0 LXP 0 00002,52     0 CAL 2 63335,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00
66552     0 CAL 3 47034,00     0 FUO 2 44012,00     0 TRA 0 66556,00     0 TRA 0 66562,00     0 LXM 0 00001,74
66557     0 CLA 0 00006,00     0 TRM 0 64161,00     0 TRA 0 66601,00     0 LXM 0 00001,74     0 LXP 0 00003,52
66564     0 CLA 0 00000,00     0 STI 0 47034,00     0 CLA 0 45777,00     0 TRM 0 64570,00     0 CLA 0 00001,00
66571     0 STL 2 47034,00     0 LXP 0 00001,52     0 CAL 2 63335,00     0 STI 0 47034,00     0 CLA 0 45777,00
66576     0 TRM 0 64570,00     0 CAL 2 47034,00     0 TRM 0 64134,00     0 LXM 0 00001,74     0 TRA 0 62110,00
66603     0 CAL 0 00054,00     0 UNL 2 63251,00     0 TRM 0 64134,00     0 TRA 0 62110,00     0 ADX 0 00001,74
66610     0 CAL 2 63337,00     0 STL 0 63346,00     0 CAL 2 63335,00     0 STL 0 63347,00     0 TRM 0 64024,00
66615     0 LXP 0 00001,52     0 TRM 0 62472,00     0 TRA 0 62110,00     0 CAL 2 44333,00     0 SUB 0 00001,00
66622     0 STL 0 44333,00     0 CAL 3 00040,00     0 STI 0 00071,00     0 SUX 0 00001,40     0 CAL 3 00041,00
66627     0 STL 0 45777,00     0 SUX 0 00001,41     0 TRA 0 62110,00     0 CAL 2 63335,00     0 STL 0 47022,00
66634     0 CLA 0 00000,00     0 STL 0 47023,00     0 CAL 2 44012,00     0 STL 0 47024,00     0 CLA 0 00000,00
```

```
66641     0 STL 0 47025,00    0 CLA 0 45777,00    0 TRM 0 64626,00    0 TRA 0 62110,00    0 CLA 0 05300,00
66646     0 UNL 2 63166,00    0 TRM 0 64320,00    0 TRA 0 62110,00


37000    00000065616  00000065621  00000065630  00000065647  00000065674  00000065720  00000065734  00000065747
37010    00000065753  00000066015  00000066057  00000066070  00000066101  00000066112  00000066123  00000066131
37020    00000066134  00000066173  00000066204  00000066215  00000066226  00000066276  00000066301  00000066343
37030    00000066400  00000066467  00000066545  00000066603  00000066607  00000066620  00000066632  00000066645
37040    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37050    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37060    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37070    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37100    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37110    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37120    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37130    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37140    30000000000  30000000000  30000000000  30000000000

         TIME USED!  00!00!29    PAGES USED!    5            19!14!50
```

Appendix D

BNF Syntax of the Formal Semantic Language

```
<program head>  :: =  BEGIN  <declaration part> ; <sentence> |
                             <program head> ; <sentence

<semantic program>  :: =  <program head> END

<declaration part>  :: =  <declaration> | <declaration part> ;
                          <declaration>

<declaration>  :: =  <table dec> | <stack dec> | <cell dec> | <title dec> |
                     <data dec>

<table dec>  :: =  TABLE <table specifier> | RTABL <table specifier> |
                     <table dec> , <table specifier>

<stack dec>  :: =  STACK <identifier list> | RSTAK <identifier list>

<cell dec>  :: =  CELL <identifier list>

<title dec>  :: =  TITLE <identifier list>

<data dec>  :: =  DATA <identifier list>

<table specifier>  :: =  <table id>  [<integer> , <integer>]

<sentence>  :: =  <integer> ↓ <statement sequence> ↓

<statement sequence>  :: =  <statement> | <statement sequence> ;
                              <statement> | CODE (<statement sequence>)

<statement>  :: =  <unconditional> | <conditional> | '<label>'
                     <statement>

<unconditional>  :: =  <assignment> | <storage> | <transfer> |
                         <auxiliary> | CODE (<unconditional>)

<conditional>  :: =  <if clause>  <statement sequence> $ |
                     <if clause>  <statement sequence> :
                     <statement sequence> $ | CODE (<conditional>)

<assignment>  :: =  <left side> ← <arithmetic> |
                    <left side> ← <boolean>
```

```
<left side>  :: =  <primary> | VALUE1 | VALUE2 | VALUE3

<storage>  :: =  <stack command> | <enter>

<stack command>  :: = PUSH [<stack id> , <arithmetic>] |
                      POP [<stack id> , <arithmetic>] .

<enter>  :: =  ENTER [<table id> ; <expression list>]

<expression list>  :: =  <arithmetic> | <expression list> , <arithmetic>

<transfer>  :: =  JUMP [<arithmetic>] | MARKJUMP  [<arithmetic>] |
                  JUMP [<label>] | MARKJUMP [<subroutine>] |
                  EXECUTE [<arithmetic>]

<auxiliary>  :: =  SET [<arithmetic> , <data id>] |
                   FAULT <identifier> | TALLY [<arithmetic>]  |
                   MINUS [<arithmetic>] | ASSIGN [<arithmetic>] |  STOP

<operand>  :: = <<arithmetic>> | COMT␣<identifier> | RUNT␣<identifier> |
                <production operand> | <storage operand>

<production operand>  :: =  LEFT1 | LEFT2 | LEFT3 | LEFT4 | LEFT5 | RIGHT1 |
                            RIGHT2 | RIGHT3

<storage operand>  :: =  <table operand> | <cell id> | <stack id> |
                         <title id>

<table operand>  :: =  <table id> [<arithmetic> <commas> $ <commas>]

<commas>  :: =  , | <commas> , | <empty>

<primary>  :: =  <operand> | <constant> | (<arithmetic>) | LOC[<table id>] |
                 LOC [<stack id>] |  <system cell> |  <flad>

<system cell>  :: =  CODELOC | STORLOC | TEMPLOC

<factor>  :: =  <primary> |  <factor> ↑ <primary>

<term>  :: =  <factor> | <term>  < */ > <factor>

<arithmetic>  :: =  <term> | < ± > <term> | <arithmetic> < ± > <term> |
                    INT [<arithmetic>] | ABS [<arithmetic>] |
                     LOC [<arithmetic>] | CHAIN [<arithmetic>]
```

```
<boolean primary>  :: =  <arithmetic> <relation> <arithmetic> |
                          <operand> |  (<boolean>) | TRUE | FALSE | SIGNAL |
                          TEST [<arithmetic> , <data id>] |
                          CONST [<arithmetic>] |  OK

<boolean factor>  :: =  <boolean primary> | ¬ <boolean primary>

<boolean term>  :: =  <boolean factor> | <boolean term> ∧ <boolean factor>

<boolean>  :: =  <boolean term> | <boolean> ∨ <boolean term>

<if clause>  :: =  <boolean> →

<stack id>  :: =  <identifier>

<data id>  :: =  <identifier>

<table id>  :: =  <identifier>

<cell id>  :: =  <identifier>

<title id>  :: =  <identifier>

<label>  :: =  <identifier>

<identifier>  :: =  <letter> | <identifier> <letter> | <identifier> <digit>

<identifier list>  :: =  <identifier> | <identifier list> , <identifier>

<subroutine>  :: =  SIN | COS | EXP | LOG | ARCTAN | SIGN |

<flad>  :: =  FLAD1 | FLAD2 | FLAD3 | FLAD4

<relation>  :: =   = | > | < | ≠
```

Appendix E

Productions for the Formal Semantic Language

```
*        SYMBOLS
*         18 INTERNAL SYMBOLS
                           I
                           OP
                           AP
                           AF
                           AT
                           AE
                           TL
                           LO
                           BP
                           BS
                           BF
                           BE
                           IC
                           UN
                           UQ
                           S
                           SQ
                           |→
     +                     +
     -                     -
     *                     *
     /                     /
     =                     =
     ≠                     ≠
     <                     <
     >                     >
     ¬                     ¬
     ∨                     ∨
     ∧                     ∧
     ↑                     ↑
     ↓                     ↓
     .                     .
     ,                     ,
     ;                     ;
     :                     :
     ←                     ←
     →                     →
     $                     $
     (                     (
     [                     [
     ]                     ]
     )                     )
     '                     '
     BEGIN                 BEGN
     END                   END
     STOP                  STOP
     STACK                 STAK
     CELL                  CELL
     TITLE                 NAME
     TABLE                 TABL
     DATA                  DATA
```

JUMP	TR
MARKJUMP	TM
EXECUTE	X
ENTER	E
PUSH	ST
POP	RS
CHAIN	CH
ASSIGN	UC
CODE	CD.
FAULT	FALT
TALLY	TAL
MINUS	MIN
SET	SET
TEST	TEST
INT	IN
LOC	L
CODELOC	A
STORLOC	W
TEMPLOC	TLOC
COMT	CT
RUNT	RT
VALUE1	V1
VALUE2	V2
VALUE3	V3
LEFT1	Y1
LEFT2	Y2
LEFT3	Y3
LEFT4	Y4
LEFT5	Y5
RIGHT1	Z1
RIGHT2	Z2
RIGHT3	Z3
FLAD1	FL1
FLAD2	FL2
FLAD3	FL3
FLAD4	FL4
SIGNAL	SIG
RSTAK	RSTK
RTABL	RTAB
CONST	CON
CLEAR	CLE
OK	OK
PLACE	PLAC
DEPTH	DEP
SAR	SAR
SIN	SIN
COS	COS
EXP	EXP
LN	LN
SQRT	SQRT
ARCTAN	ARC
SIGN	SIGN
TRUE	TRUE
FALSE	FALS

* METACHARACTERS

```
M  <TD>  * /
M  <PM> + -
M  <RL> = < > ≠
M  <EN> = < > ≠ ] ) ; . ↑ ↓
M  <BN> ^ ˅ ¬
M  <TP> TABL STAK CELL NAME   DATA RSTK RTAB
M  <V> V1 V2 V3
M  <Y>  Y1 Y2 Y3 Y4 Y5
M  <Z> Z1 Z2 Z3
M  <FL> FL1 FL2 FL3 FL4
M <CO> TR TM TAL MIN X CH UC ST RS SET CON CLE
M  <EN> = <  > ≠ ]  ) ; $ ↑ ↓
M  <AR> + - * / = < >  ≠
M  <SH> SAR SIN COS EXP LN SQRT ARC SIGN
*       ACTIONS

    EXEC
    NSTK
    STAK
    VALU
    SUBR
    SCAN
    NEXT
    GET
    BOOK
    RETURN
    ERROR
    HALT
    CON
    NUM
    FOUT
    STRIN
*       PRODUCTION TABLE
37621   00000000170  00053117163  00003754224  00003560231  00611714205  00003606376  00000000712  00000017105
37631   00000011111  00000063366  00000062722  00035514621  00164555471  00000001066  00027626043  00030330167
37641   00204435745  00204355575  11743611142  00055161016  00055161015  00055161014  00055161013  11333155110
37651   11333155107  11333155106  00126625667  00126625666  00126625665  00126625664  00126625663  13305117277
37661   13305117276  13305117275  00003455761  00000521703  20000006000  12320674355  20000006000  12063765243
37671   20000006000  01605475232  00000041132  00000031073  00003711324  00000063150  00136603374  00217175262
37701   00053146640  00000521147  00624052521  00027000157  00000053713  00003150344  00046435212  20000012000
37711   02727146472  20001742000  06571415646  00002026340  00000617662  00217142444  00220652116  00000467034
37721   00213552372  00003616226  00000016307  00017232775  00000000077  00000000073  00000000072  00000000071
37731   00000000070  00000000065  00000000035  00000000034  00000000076  00000000067  00000000037  00000000053
37741   00000000074  00000000075  00000000063  00000000061  00000000036  00000000066  00000000064  00000000062
37751   00000000060  00000000057  00000000056  00000000055  00000000054  30000000000  30000000000  30000000000
37761   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37771   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  00000000355
40001   30000000000  02000000053  00000000031  00000000103  30000000000  02000000156  00000000221  30000000000
40011   30000000000
...
```

```
D0                            BEGN  |                  |  EXEC 1      *D1
                              <SG>  |                  |  ERROR 0     Q2
D1                            <TP>  |                  |  SCAN        *D2
                              ↓     |                  |              *S1
                              END   | →                |  HALT        D1
                              I     | →                |  EXEC 2      *D1
                              <SG>  |                  |  ERROR 1     Q2
D2                <TP>  I     ,     | →          <TP>  |  EXEC 3      D1
                  <TP>  I     ;     | →                |  EXEC 3      *D1
                              [     | →                |  SCAN        *TA
                              <SG>  |                  |  ERROR 2     Q2
TA          TABL  I     I     ,     |                  |  SCAN        *TA1
TA1   I     I     ,     I     ]     | →                |  EXEC 4      *TA2
TA2                     TABL  ,     | →          TABL  |              D1
                        TABL  ;     | →                |              *D1
                        TABL  <SG>  | →          <SG>  |              D1
                              <SG>  |                  |  ERROR 3     Q2
S1                            <CO>  |                  |  SCAN        *AP1
                              E     |                  |  SCAN        *SP1
                              <V>   |                  |  SCAN        *EX1
                              CD.   |                  |  EXEC 5      *CD
                              FALT  |                  |              *F1
                              STOP  | →          UN    |  EXEC 57     *UN
                              '     |                  |  SCAN        *LAB
                              ;     | →                |              *S1
                        I     ↓     | →                |  ERROR 19    *S1
EX1                           ¬     |                  |              *EX1
                              OK    | →          BP    |  EXEC 6      *BS1
                              W     | →          OP    |  EXEC 15     *OP1
                              TLOC  | →          OP    |  EXEC 16     *OP1
                              SIG   | →          BP    |  EXEC 17     *BS1
                              TEST  |                  |  SCAN        *AP1
                              <SG>  |                  |              AP1
LAB               '     I     '     | →                |  EXEC 7      *S1
OP1               <AR>  OP    <SG>  | → <AR> AP  <SG>  |              AF1
                        OP    <BN>  | →      BP  <BN>  |              BS1
                        OP    <SG>  | →      AP  <SG>  |              AF1
                              <SG>  |                  |  ERROR 5     Q1
ID          L     [     I     ]     | →          OP    |  EXEC 58     *OP1
                  [     I     ]     | → [    AE  ]     |  EXEC 8      AE3
                  ←     I     <EN>  | → ←    AE  <EN>  |  EXEC 8      AE2
            TL    [     I     ,     | → TL   AE  ,     |  EXEC 9      T0
                        I     [     | →      TL  [     |  EXEC 10     *AP1
                        I     <SG>  | →      OP  <SG>  |  EXEC 11     OP1
                              <SG>  |                  |  ERROR 6     Q1
B1                      CT    I     | →          OP    |  EXEC 12     *OP1
                        RT    I     | →          OP    |  EXEC 13     *OP1
                              <SG>  |                  |  ERROR 7     Q1
CD                      CD.   (     | →          CD.   |              *S1
                              <SG>  |                  |  ERROR 4     Q1
AP1                           (     |                  |              *EX1
                              I     |                  |              *ID
                              <PM>  |                  |              *AP1
                              IN    |                  |  SCAN        *AP1
                              L     |                  |  SCAN        *AP1
```

```
                                CH     |                         |   SCAN        *AP1
                                CT     |                         |               *B1
                                RT     |                         |               *B1
                                A      | →              AP       |   EXEC 14     *AF1
                                W      | →              AP       |   EXEC 15     *AF1
                                TLOC   | →              AP       |   EXEC 16     *AF1
                                <CO>   |                         |   SCAN        *AP1
                                <SR>   | →              AE       |   EXEC 18     *AE3
                                <Y>    | →              OP       |   EXEC 19     *OP1
                                <Z>    | →              AP       |   EXEC 20     *AF1
                                <      |                         |               *AP1
                                PLAC   | →              AE       |   EXEC 49     *AE2
                                <FL>   | →              AP       |   EXEC 22     *AF1
                                DEP    | →              AP       |   EXEC 66     *AF1
                                <SG>   |                         |   ERROR 18    Q1
AF1       AF     ↑       AP     <SG>   | →       AF     <SG>     |   EXEC 21     AF2
                         AP     ←      |                         |               *EX1
                         AP     <SG>   | →       AF     <SG>     |               AF2
AF2                      AF     ↑      |                         |               *AP1
AT1       AT     <TD>    AF     <SG>   | →       AT     <SG>     |   EXEC 23     AT2
                         AF     <SG>   | →       AT     <SG>     |               AT2
AT2                      AT     <TD>   |                         |               *AP1
AE1       AE     <PM>    AT     <SG>   | →       AE     <SG>     |   EXEC 24     AE2
                 +       AT     <SG>   | →       AE     <SG>     |               AE2
                 -       AT     <SG>   | →       AE     <SG>     |   EXEC 25     AE2
                         AT     <SG>   | →       AE     <SG>     |               AE2
                                <SG>   |                         |   ERROR 8     Q1
AE2                      AE     <PM>   |                         |               *AP1
                         AE     ]      |                         |               AE3
                 <       AE     >      | →              OP       |   EXEC 26     *OP1
                         AE     <RL>   |                         |               *AP1
                 (       AE     )      | →              AP       |   EXEC 27     *AF1
          TL     [       AE     ,      | →   TL  AE     ,        |               T0
                 [       AE     ,      | →              AE       |   EXEC 27     *AP1
          E      TL      AE     ,      | →       E      TL       |   EXEC 28     *EX1
          AE     <RL>    AE     <SG>   | →       BP     <SG>     |   EXEC 29     BS1
          AP     ←       AE     <SG>   | →       UN     <SG>     |   EXEC 30     UN
          <V>    ←       AE     <SG>   | →       UN     <SG>     |   EXEC 31     UN
                         AE     <SG>   | →       BP     <SG>     |               BS1
AE3       IN     [       AE     ]      | →              AE       |   EXEC 32     *AE2
          TR     [       AE     ]      | →              UN       |   EXEC 33     *UN
          TM     [       AE     ]      | →              UN       |   EXEC 34     *UN
          L      [       AE     ]      | →              AP       |   EXEC 35     *AF1
          X      [       AE     ]      | →              UN       |   EXEC 36     *UN
          TAL    [       AE     ]      | →              UN       |   EXEC 37     *UN
          MIN    [       AE     ]      | →              UN       |   EXEC 38     *UN
          CH     [       AE     ]      | →              AE       |   EXEC 39     *AE2
          UC     [       AE     ]      | →              UN       |   EXEC 40     *UN
          CON    [       AE     ]      | →              BP       |   EXEC 64     *BS1
          CLE    [       AE     ]      | →              UN       |   EXEC 65     *UN
          ST     AE      AE     ]      | →              UN       |   EXEC 41     *UN
          RS     AE      AE     ]      | →              UN       |   EXEC 42     *UN
          SET    AE      AE     ]      | →              UN       |   EXEC 54     *UN
          TEST   AE      AE     ]      | →              BP       |   EXEC 56     *BS1
          E      TL      AE     ]      | →              UN       |   EXEC 43     *UN
```

```
                              <SG>   |                   |  ERROR 9     Q1
BS1              ¬     BP     <SG>   |  →   BS    <SG>   |  EXEC 44     BF1
                       BP     <SG>   |  →   BS    <SG>   |              BF1
BF1         BF   ^     BS     <SG>   |  →   BF    <SG>   |  EXEC 45     BF2
                       BS     <SG>   |  →   BF    <SG>   |              BF2
BF2                    BF     ^      |                   |              *EX1
BE1         BE   ˅     BF     <SG>   |  →   BE    <SG>   |  EXEC 46     BE2
                       BF     <SG>   |  →   BE    <SG>   |              BE2
                              <SG>   |                   |  ERROR 10    Q1
BE2                    BE     ˅      |                   |              *EX1
                       BE     →      |  →         IC     |  EXEC 47     *S1
                 (     BE     )      |  →         BP     |  EXEC 48     *BS1
            <V>  ←     BE     <SG>   |  →   UN    <SG>   |  EXEC 31     UN
            AP   ←     BE     <SG>   |  →   UN    <SG>   |  EXEC 50     UN
                              <SG>   |                   |  ERROR 11    Q1
UN                     UN     <SG>   |  →   S     <SG>   |              S9
                              <SG>   |                   |  ERROR 12    Q1
S9          SQ   ;     S      <SG>   |  →   SQ    <SG>   |              SQ1
      IC    SQ   '     S      $      |  →         S      |  EXEC 53     *S9
                 CD.   S      )      |  →         S      |  EXEC 52     *S9
                       S      <SG>   |  →   SQ    <SG>   |              SQ1
                              <SG>   |                   |  ERROR 13    Q1
SQ1   IC    SQ   '     SQ     $      |  →         S      |  EXEC 53     *S9
                 CD.   SQ     )      |  →         S      |  EXEC 52     *S9
                 ↓     SQ     ↓      |  →                |  EXEC 59     *D1
                 IC    SQ     :      |                   |  EXEC 55     *S1
                 IC    SQ     $      |  →         S      |  EXEC 51     *S9
                       SQ     ;      |                   |              *S1
                              <SG>   |                   |  ERROR 15    Q1
SP1              E     [      I      |  →   E     TL     |  EXEC 63     *SP2
SP2                    TL     ;      |  →         TL     |              *EX1
                              <SG>   |                   |  ERROR 16    Q1
T0               TL    AE     ,      |  →   TL    AE     |  EXEC 60     *T0
                 TL    AE     $      |  →         OP     |  EXEC 61     *T1
T1                            ,      |  →                |              *T1
                              ]      |  →                |              *OP1
                              <SG>   |                   |  ERROR 17    Q1
Q1                            ↓      |  →                |              *D1
                              END    |                   |  HALT        Q1
                              <SG>   |  →                |              *Q1
Q2                            ↓      |                   |              D1
                              END    |                   |  HALT        Q1
                              <SG>   |  →                |              *Q2
F1                     FALT   <SG>   |  →         UN     |  EXEC 62     *UN
                              <SG>   |                   |  ERROR 20    Q1
*           END

OTHER STUFF
I 1              4
I 2              0
I 3              0
I 4              0
I 5              0
I 6             20
```

```
I 7          62
I 8          67
I 9           0
I10           1
I11          67
I12           6
I13          15
I14           3
I15           0
I16          36
I17           2
I18         565
I19    *        0
I20          28
I21       16273
J 0         492
J 1           0
J 2           1
J 3          65
J 4          67
J 5           3
J 6          51
J 7          18


              LABEL TABLE

         LABEL NAME     VALUE
  1        D0               0
  2        D1               4
  3        Q2             481
  4        D2              14
  5        S1              48
  6        TA              26
  7        TA1             31
  8        TA2             37
  9        AP1            136
 10        SP1            452
 11        EX1             67
 12        CD             131
 13        F1             487
 14        UN             400
 15        LAB             81
 16        BS1            350
 17        OP1             85
 18        AF1            176
 19        Q1             475
 20        ID              97
 21        AE3            268
 22        AE2            219
 23        T0             461
 24        B1             123
 25        AF2            187
 26        AT1            190
 27        AT2            198
 28      AE1          201
 29      BF1          357
 30      BF2          365
 31      BE1          368
 32      BE2          378
 33      S9           405
 34      SQ1          425
 35      SP2          456
 36      T1           469
 37                     1

          PRODUCTION TABLE
62245   01050210000  00000000253  01050210003  00000000000  01050210005  01050700026  01050210010  00000000236
62255   01050210012  00000000254  01050210015  00000000200  01050210021  00000000000  01050410023  00000000240
62265   00000000200  01050700026  01050410026  00000000241  00000000200  01050700026  01050210032  00000000247
62275   01050210036  00000000000  01050510040  00000000240  00000000200  00000000200  00000000261  01050610043
62305   00000000250  00000000200  00000000240  00000000200  00000000200  01050310047  00000000240  00000000261
62315   01050310051  00000000241  00000000261  01050310054  00000000000  00000000261  01050210057  00000000000
62325   01050210061  01051400054  01050210064  00000000270  01050210067  01050300035  01050210072  00000000275
62335   01050210075  00000000276  01050210077  00000000255  01050210104  00000000252  01050210107  00000000241
62345   01050310112  00000000236  00000000200  01050210116  00000000232  01050210120  00000000341  01050210125
62355   00000000310  01050210132  00000000312  01050210137  00000000334  01050210144  00000000302  01050210147
62365   00000000000  01050410150  00000000252  00000000200  00000000252  01050410154  00000000000  00000000201
62375   01051000102  01050310160  01050300023  00000000201  01050310164  00000000000  00000000201  01050210170
62405   00000000000  01050510172  00000000250  00000000200  00000000247  00000000304  01050410177  00000000250
62415   00000000200  00000000247  01050410204  01051200011  00000000200  00000000243  01050510211  00000000240
62425   00000000200  00000000247  00000000206  01050310216  00000000247  00000000200  01050310224  00000000000
62435   00000000200  01050210231  00000000000  01050310233  00000000200  00000000313  01050310240  00000000200
62445   00000000314  01050210245  00000000000  01050310247  00000000246  00000000275  01050210252  00000000000
62455   01050210254  00000000246  01050210256  00000000200  01050210260  01050200003  01050210262  00000000303
62465   01050210265  00000000304  01050210270  00000000273  01050210273  00000000313  01050210275  00000000314
62475   01050210277  00000000306  01050210304  00000000310  01050210311  00000000312  01050210316  01051400054
62505   01050210321  01051000112  01050210326  01050500040  01050210333  01050300045  01050210340  00000000230
62515   01050210342  00000000342  01050210347  01050400050  01050210354  00000000343  01050210361  00000000000
62525   01050510363  00000000000  00000000202  00000000235  00000000203  01050310367  00000000243  00000000202
62535   01050310371  00000000000  00000000202  01050310375  00000000235  00000000203  01050510377  00000000000
62545   00000000203  01050200001  00000000204  01050310403  00000000000  00000000203  01050310407  01050200001
62555   00000000204  01050510411  00000000000  00000000204  01050200003  00000000205  01050410415  00000000000
62565   00000000204  00000000222  01050410421  00000000000  00000000204  00000000223  01050310426  00000000000
62575   00000000204  01050210432  00000000000  01050310434  01050200003  00000000205  01050310436  00000000250
62605   00000000205  01050410437  00000000231  00000000205  00000000230  01050310444  01050400005  00000000205
62615   01050410446  00000000251  00000000205  00000000246  01050510453  00000000240  00000000205  00000000247
62625   00000000206  01050410457  00000000240  00000000205  00000000247  01050510464  00000000240  00000000205
62635   00000000206  00000000270  01050510470  00000000000  00000000205  01050400005  00000000205  01050510475
62645   00000000000  00000000205  00000000243  00000000202  01050510502  00000000000  00000000205  00000000243
62655   01050300035  01050310507  00000000000  00000000205  01050510513  00000000250  00000000205  00000000247
62665   00000000303  01050510520  00000000250  00000000205  00000000247  00000000263  01050510525  00000000250
62675   00000000205  00000000247  00000000265  01050510532  00000000250  00000000205  00000000247  00000000304
62705   01050510537  00000000250  00000000205  00000000247  00000000267  01050510544  00000000250  00000000205
62715   00000000247  00000000277  01050510551  00000000250  00000000205  00000000247  00000000300  01050510556
62725   00000000250  00000000205  00000000247  00000000273  01050510563  00000000250  00000000205  00000000247
62735   00000000274  01050510570  00000000250  00000000205  00000000247  00000000337  01050510575  00000000250
62745   00000000205  00000000247  00000000340  01050510602  00000000250  00000000205  00000000205  00000000271
62755   01050510607  00000000250  00000000205  00000000205  00000000272  01050510614  00000000250  00000000205
62765   00000000205  00000000301  01050510621  00000000250  00000000205  00000000205  00000000302  01050510626
```

```
62775   00000000250  00000000205  00000000206  00000000270  01050210633  00000000000  01050410635  00000000000
63005   00000000210  00000000232  01050310642  00000000000  00000000210  01050510646  00000000000  00000000211
63015   00000000234  00000000212  01050310652  00000000000  00000000211  01050310656  00000000234  00000000212
63025   01050510660  00000000000  00000000212  00000000233  00000000213  01050310664  00000000000  00000000212
63035   01050210670  00000000000  01050310672  00000000233  00000000213  01050310674  00000000244  00000000213
63045   01050410701  00000000251  00000000213  00000000246  01050510706  00000000000  00000000213  00000000243
63055   01050300035  01050510713  00000000000  00000000213  00000000243  00000000202  01050210720  00000000000
63065   01050310722  00000000000  00000000215  01050210726  00000000000  01050510730  00000000000  00000000217
63075   00000000241  00000000220  01050610733  00000000245  00000000217  00000000242  00000000220  00000000214
63105   01050410740  00000000251  00000000217  00000000275  01050310745  00000000000  00000000217  01050210751
63115   00000000000  01050610753  00000000245  00000000220  00000000242  00000000220  00000000214  01050410760
63125   00000000251  00000000220  00000000275  01050410765  00000000236  00000000220  00000000236  01050410771
63135   00000000242  00000000220  00000000214  01050410774  00000000245  00000000220  00000000214  01050311001
63145   00000000241  00000000220  01050211003  00000000000  01050411005  00000000200  00000000247  00000000270
63155   01050311012  00000000241  00000000206  01050211015  00000000000  01050411017  00000000240  00000000205
63165   00000000206  01050411023  00000000245  00000000205  00000000206  01050211030  00000000240  01050211033
63175   00000000250  01050211036  00000000000  01050211040  00000000236  01050211043  00000000254  01050211045
63205   00000000000  01050211050  00000000236  01050211051  00000000254  01050211053  00000000000  01050311056
63215   00000000000  00000000276  01050211063  00000000000  30000000000

          AUXILIARY PRODUCTION TABLE
65202   00100000000  00000000000  00000000215  00000000201  00000000205  00000000217  00000000240  30000000000
65212   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
65222   30000000000  30000000000  30000000000  30000000000

          INTERPRETATION TABLE
65227   00010000001  00060000001  00070000004  00130000000  00070000741  00060000000  00060000001  00070000016
65237   00060000001  00070000060  00020000001  00140000000  00070000004  00020000001  00010000002  00060000001
65247   00070000004  00130000001  00070000741  00020000002  00010000003  00070000004  00020000003  00010000003
65257   00060000001  00070000004  00020000001  00060000000  00060000001  00070000032  00130000002  00070000741
65267   00060000000  00060000001  00070000037  00020000005  00010000004  00060000001  00070000045  00020000001
65277   00070000004  00020000002  00060000001  00070000004  00020000002  00030000000  00070000004  00130000003
65307   00070000741  00060000000  00060000001  00070000210  00060000000  00060000001  00070000704  00060000000
65317   00060000001  00070000103  00010000005  00060000001  00070000203  00060000001  00070000747  00020000001
65327   00030000215  00010000071  00060000001  00070000620  00060000000  00060000001  00070000121  00020000001
65337   00060000001  00070000060  00020000002  00130000023  00060000001  00070000060  00060000001  00070000103
65347   00020000001  00030000210  00010000006  00060000001  00070000536  00020000001  00030000201  00010000017
65357   00060000001  00070000125  00020000001  00030000201  00010000020  00060000001  00070000125  00020000001
65367   00030000210  00010000021  00060000001  00070000536  00060000000  00060000001  00070000210  00070000210
65377   00020000003  00010000007  00060000001  00070000060  00020000002  00030000202  00030000000  00070000260
65407   00020000002  00030000210  00030000000  00070000536  00020000002  00030000202  00030000000  00070000260
65417   00130000005  00070000733  00020000004  00030000201  00010000072  00060000001  00070000125  00020000002
65427   00030000205  00030000000  00010000010  00070000414  00020000002  00030000205  00030000000  00010000010
65437   00070000333  00020000003  00030000205  00030000000  00010000011  00070000715  00020000002  00030000206
65447   00030000000  00010000012  00060000001  00070000210  00020000002  00030000201  00030000000  00010000013
65457   00070000125  00130000006  00070000733  00020000002  00030000201  00010000014  00060000001  00070000125
65467   00020000002  00030000201  00010000015  00060000001  00070000125  00130000007  00070000733  00020000001
65477   00060000001  00070000060  00130000004  00070000733  00060000001  00070000103  00060000001  00070000141
65507   00060000001  00070000210  00060000000  00060000001  00070000210  00060000000  00060000001  00070000210
65517   00060000000  00060000001  00070000210  00060000001  00070000173  00060000001  00070000173  00020000001
65527   00030000202  00010000016  00060000001  00070000260  00020000001  00030000202  00010000017  00060000001
65537   00070000260  00020000001  00030000202  00010000020  00060000001  00070000260  00060000000  00060000001
65547   00070000210  00020000001  00030000205  00010000022  00060000001  00070000414  00020000001  00030000201
65557   00010000023  00060000001  00070000125  00020000001  00030000202  00010000024  00060000001  00070000260
65567   00060000001  00070000210  0002000000   00030000205  00010000061  00060000001  00070000333  00020000001
```

```
655/7     00030000202  00010000026  00060000001  00070000260  00020000001  00030000202  00010000102  00060000001
65607     00070000260  00130000022  00070000733  00020000003  00030000000  00010000025  00070000273  00060000001
65617     00070000103  00020000002  00030000203  00030000000  00070000273  00060000001  00070000210  00020000003
65627     00030000000  00010000027  00070000306  00020000002  00030000204  00030000000  00070000306  00060000001
65637     00070000210  00020000003  00030000000  00010000030  00070000333  00020000003  00030000205  00030000000
65647     00070000333  00020000003  00030000205  00030000000  00010000031  00070000333  00020000002  00030000205
65657     00030000000  00070000333  00130000010  00070000733  00060000001  00070000210  00070000414  00020000003
65667     00030000201  00010000032  00060000001  00070000125  00060000001  00070000210  00020000003  00030000202
656/7     00010000033  00060000001  00070000260  00020000003  00030000001  00030000000  00070000715  00020000003
65707     00030000001  00010000033  00060000001  00070000210  00020000002  00010000034  00060000001  00070000103
65717     00020000004  00030000210  00030000000  00010000035  00070000536  00020000004  00030000215  00030000000
65727     00010000036  00070000620  00020000004  00030000215  00030000000  00010000037  00070000620  00020000002
65737     00030000210  00030000000  00070000536  00020000004  00030000001  00010000040  00060000001  00070000333
65747     00020000004  00030000215  00010000041  00060000001  00070000620  00020000004  00030000215  00010000042
65757     00060000001  00070000620  00020000004  00030000202  00010000043  00060000001  00070000260  00020000004
65767     00030000215  00010000044  00060000001  00070000620  00020000004  00030000215  00010000045  00060000001
657/7     00070000620  00020000004  00030000215  00010000046  00060000001  00070000620  00020000004  00030000001
66007     00010000047  00060000001  00070000333  00020000004  00030000215  00010000050  00060000001  00070000620
66017     00020000004  00030000210  00010000100  00060000001  00070000536  00020000004  00030000215  00010000101
66027     00060000001  00070000620  00020000004  00030000215  00010000051  00060000001  00070000620  00020000004
66037     00030000215  00010000052  00060000001  00070000620  00020000004  00030000215  00010000066  00060000001
66047     00070000620  00020000004  00030000210  00010000070  00060000001  00070000536  00020000004  00030000215
66057     00010000053  00060000001  00070000620  00130000011  00070000733  00020000003  00030000211  00030000000
66067     00010000054  00070000545  00020000002  00030000211  00030000000  00070000545  00020000003  00030000000
660/7     00010000055  00070000555  00020000002  00030000212  00030000000  00070000555  00060000001  00070000103
66107     00020000003  00030000000  00010000056  00070000572  00020000002  00030000213  00030000000  00070000572
66117     00130000012  00070000733  00060000001  00070000103  00020000002  00030000214  00010000057  00060000001
66127     00070000060  00020000003  00030000210  00010000060  00060000001  00070000536  00020000004  00030000215
66137     00030000000  00010000037  00070000620  00020000004  00030000215  00030000000  00010000062  00070000620
66147     00130000013  00070000733  00020000002  00030000217  00030000000  00070000625  00130000014  00070000733
66157     00020000003  00030000000  00070000651  00020000005  00030000001  00010000065  00060000001  00070000625
66167     00020000003  00030000001  00010000064  00060000001  00070000625  00020000002  00030000220  00030000000
661/7     00070000651  00130000015  00070000733  00020000005  00030000217  00010000065  00060000001  00070000625
66207     00020000003  00030000217  00010000064  00060000001  00070000625  00020000003  00010000073  00060000001
66217     00070000004  00010000067  00060000001  00070000060  00020000003  00030000217  00010000063  00060000001
66227     00070000625  00060000001  00070000060  00130000017  00070000733  00020000002  00030000206  00010000077
66237     00060000001  00070000710  00020000001  00060000001  00070000103  00130000020  00070000733  00020000001
66247     00010000074  00060000001  00070000715  00020000003  00030000201  00010000075  00060000001  00070000725
66257     00020000001  00060000001  00070000725  00020000001  00060000001  00070000125  00130000021  00070000733
66267     00020000001  00060000001  00070000004  00140000000  00070000733  00020000001  00060000001  00070000733
66277     00070000004  00140000000  00070000733  00020000001  00060000001  00070000741  00020000002  00030000215
66307     00010000076  00060000001  00070000620  00130000024  00070000733
*          TAPE 8    4
               RECORD TYPE              NUMBER OF RECORDS   STARTING RECORD

           SYMBOL TABLE                         1                  8
           HIERARCHY TABLE                      2                  9
           PRODUCTION TABLE                     1                 13
           METACHARACTER LISTS                  2                 14

          TIME USED:  00:05:02     PAGES USED:   11              19:08:18
```

Appendix F

This appendix consists of three sample programs written in the small language and translated by the compiler built from Appendices B and C. None of the programs are meant to do useful computations, but rather to illustrate the functioning of the compiler.

Example 1 is a correct program involving fairly complicated uses of conditional and arithmetic statements. Example 2 is somewhat simpler, but has been run with several trace options on. Example 3 contains an example of a semantic error, as well as some fairly complex code. The interested reader can get a good idea of the type of code produced by the system from these examples. However, the lack of really involved structures (procedures, etc.) in the small language may yield an unrealistically optimistic picture of the sytem's performance.

```
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OPERATOR-040 14 MAY 64  19:10:11  MAGIC  PAGES:  50  TIME:   1                       CC35.013     J. FELDMAN
                                                                                                COMPUTER CENTER

                                                         00:00:04①

CO                     EXAMPLE 1
SN         DUMP 1
    BEGIN REAL X,Y,ZEBRA; BOOLEAN P,Q; LABEL L1,L2;
     L1: Y← X*Y-ZEBRA↑(Y/2) ;
       IF IF P THEN Q ELSE X=3 THEN BEGIN X← X-1; GOTO L1 END
                  ELSE GOTO L2;
       X← X+1; GOTO L1;
    L2: Q← TRUE
           END
20000     0 CLA 2 40000,00    0 MPY 2 40002,00    0 SID 0 72400,77    0 CLA 2 40002,00③  0 DIV 0 00002,00
20005     0 STD 0 72652,00    0 CLA 2 40004,00    0 STD 0 72650,00    0 TRM 0 10253,00   0 SUN 2 72400,77
20012     0 STD 0 40002,00    0 CLA 2 40000,00    0 FUO 0 00003,00    0 OCA 0 00001,00   0 CCL 2 14376,00
20017     0 IOZ 2 40006,00⑤   0 TRA 0 20024,00    0 CAL 2 40007,00    0 STL 0 72400,77   0 TRA 0 20025,00
20024     0 STL 0 72400,77    0 ICZ 2 72400,77    0 TRA 0 20030,00    0 TRA 0 20035,00   0 CLA 2 40000,00
20031     0 SUB 0 00001,00    0 STD 0 40000,00    0 TRA 0 20000,00    0 TRA 0 20036,00   0 TRA 0 20042,00
20036     0 CLA 2 40000,00    0 ADD 0 00001,00④   0 STD 0 40000,00    0 TRA 0 20000,00   0 CAL 2 14377,00
20043     0 STL 0 40007,00    0 TRM 0 05300,00


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```

1. The compiler took four seconds to read in the tables of the small language.

2. Three seconds were used to compile and dump the program.

3. ↑ is executed by a library subroutine.

4. Location 5300 is the monitor HALT routine.

5. Temporaries start at 72400; the index register allows recursive use of temporaries.

```
≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠/≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠

OPERATOR-040 14 MAY 64  19:18:37  MAGIC  PAGES:  20  TIME:   3                        CC35.013   J. FELDMAN
                                                                                                 COMPUTER CENTER


                                                 00:00:04

CO                  EXAMPLE 2
SN   ①   CODE 1
SN   ②   EXEC 1
SN        DUMP
   BEGIN REAL X,Y,ZEBRA; BOOLEAN P,Q; LABEL L1,L2;
00061    0000000001
63334    0000000252  0000000000  0000000000  0000000000  0000000000  0000000252  0000000213  0000000213
00061    0000000004
63334    0000000234  0000000262  0000000246  0000000000  0000000000  0000000234  0000000262  0000000246
00061    0000000004
63334    0000000234  0000000263  0000000246  0000000000  0000000000  0000000234  0000000263  0000000246
00061    0000000004
63334    0000000235  0000000264  0000000246  0000000000  0000000000  0000000235  0000000264  0000000246
00061    0000000005
63334    0000000234  0000000265  0000000250  0000000000  0000000000  0000000234  0000000265  0000000250
00061    0000000005
63334    0000000235  0000000266  0000000250  0000000000  0000000000  0000000235  0000000266  0000000250
00061    0000000036
63334    0000000234  0000000267  0000000251  0000000000  0000000000  0000000234  0000000267  0000000251
00061    0000000036
63334    0000000235  0000000270  0000000251  0000000000  0000000000  0000000235  0000000270  0000000251
    L1: IF (X*Y)/(X+Y) = ZEBRA THEN
00061    0000000002
63334    0000000267  0000000246  0000000252  0000000000  0000000000  0000000267  0000000235  0000000252
00061    0000000032
63334    0000000236  0000000267  0000000252  0000000000  0000000000  0000000235  0000000252  0000000213
00061    0000000011
63334    0000000262  0000000267  0000000252  0000000000  0000000000  0000000262  0000000242  0000000255
00061    0000000011
63334    0000000263  0103004000  0000000252  0000000000  0000000000  0000000263  0000000216  0103004000
00061    0000000012
63334    0000000245  0103004002  0000000216  0103004000  0000000000  0000000245  0103004000  0000000242
20000    0405004000
20001    0477004002
00061    0000000017
63334    0000000245  0003040000  0000000242  0103004000  0000000000  0000000242  0000000255  0000000235
00061    0000000011
63334    0000000262  0003040000  0000000242  0103004000  0000000000  0000000262  0000000242  0000000217
00061    0000000011
63334    0000000263  0103004000  0000000242  0103004000  0000000000  0000000263  0000000214  0103004000
00061    0000000014
63334    0000000245  0103004002  0000000214  0103004000  0000000000  0000000245  0103004000  0000000242
20002    0153777240
20003    0405004000
20004    0445004002
00061    0000000017
63334    0000000245  0003040000  0000000242  0103004000  0000000000  0000000242  0103207240  0003040000
```

```
00061   00000000013
63334   00000000220  00030400000  01032072400  00030400000  00000000000  00000000220  00030400000  00000000255
20005   00570040002
00061   00000000011
63334   00000000264  00030400000  01032072400  00030400000  00000000000  00000000264  00000000220  00030400000
00061   00000000021
63334   00000000256  01030040004  00000000220  00030400000  00000000000  00000000256  00030400000  00000000255
20005   05610040004
20007   00000000001
20010   04150014376
20010   04350014376
00061   00000000025
63334   00000000256  00000400000  00000000255  00030400000  00000000000  00000000255  00000000235  00000000252
00061   00000000003
63334   00000400000  00000400000  00000000255  00030400000  00000000000  00000400000  00000000235  00000000252
20007   00170000000
20010   00170000000
        BEGIN X← -X+ZEBRA; GOTO L2 END ELSE P← FALSE;
00061   00000000002
63334   00000000262  00000000252  00000000255  00030400000  00000000000  00000000262  00000000235  00000000252
00061   00000000011
63334   00000000262  00000000252  00000000255  00030400000  00000000000  00000000262  00000000215  00000000237
00061   00000000016
63334   00000000214  01030040000  00000000215  00030400000  00000000000  00000000214  00000000215  00000000237
00061   00000000011
63334   00000000264  01030040000  00000000215  00030400000  00000000000  00000000264  00000000214  01034040000
00061 3 00000000014                               4
63334   00000000235  01030040004  00000000214  01034040000  00000000000  00000000235  01034040000  00000000237
20011   04250040000
20012   04450040004
00061   00000000020
63334   00000000235  00030400000  00000000237  00000000262  00000000000  00000000235  00000000262  00000000235
20013   01530040000
00061   00000000031
63334   00000000270  00000000254  00000000237  00000000262  00000000000  00000000254  00000000235  00000000252
20014   00170000000
00061   00000000035
63334   00000000253  00000000254  00000000235  00000000252  00000000000  00000000252  00000400000  00000000235
00061   00000000006
63334   00000000257  00000000252  00000400000  00000000252  00000000000  00000000257  00000000252  00000400000
20015   00170000000
00061   00000000030
63334   00000000235  01000214376  00000000237  00000000265  00000000000  00000000235  00000000265  00000000257
20016   04150014376
20017   01730040006
00061   00000000033
63334   00000000235  00000000265  00000000257  00000000252  00000400000  00000000235  00000000265  00000000235
    L2: IF P THEN X← Y↑ZEBRA; Q← X<Y
00061   00000000032
63334   00000000236  00000000270  00000000257  00000000252  00000400000  00000000235  00000000252  00000000213
00061   00000000024
63334   00000000256  00000000265  00000000257  00000000252  00000400000  00000000256  00000000265  00000000255
00061   00000000025
63334   00000000256  01000040006  00000000255  00000000252  00000400000  00000000255  00000000235  00000000252
00061   00000000003
```

```
63334    01000040006  01000040006  00000000255  00000000252  00000400000  01000040006  00000000235  00000000252
20020    04310040006
20021    00170000000
20022    00170000000
00061    00000000010
63334    00000000231  00000000263  00000000255  00000000252  00000400000  00000000231  00000000263  00000000237
00061    00000000011
63334    00000000264  01030040002  00000000255  00000000252  00000400000  00000000264  00000000231  01030040002
00061    00000000034
63334    00000000235  01030040004  00000000231  01030040002  00000400000  00000000235  01030040002  00000000237
20023    04050040004
20024    01530072652
20025    04050040002
20026    01530072650
20027    01770010253
00061    00000000020
63334    00000000235  00030400000  00000000237  00000000262  00000400000  00000000235  00000000262  01000040006
20030    01530040000
00061    00000000007
63334    00000000235  00000000262  01000040006  00000000262  00000400000  00000000235  01000040006  00000000235
00061    00000000010
63334    00000000224  00000000262  01000040006  00000000262  00000400000  00000000224  00000000262  00030000237
00061    00000000011
63334    00000000263  00000000262  01000040006  00000000262  00000400000  00000000263  00000000224  01030040000
        END
00061    00000000022
63334    00000000253  01030040002  00000000224  01030040000  00000400000  00000000253  01030040000  00000000237
20031    04050040000
20032    05210040002
20033    00000000001
20034    04150014376
00061    00000000027
63334    00000000253  00000400000  00000000237  00000000266  00000400000  00000000253  00000000266  00000000235
20035    01730040007
00061    00000000035
63334    00000000253  00000000266  00000000235  00000000252  00000400000  00000000252  00000000213  00000000213
00061    00000000037
63334    00000000252  00000000213  00000000235  00000000252  00800400000  00000000213  00000000213  00000000213
20036    01770005300
20000     0 CLA 2 40000,00     0 MPY 2 40002,00     0 STD 0 72400,77     0 CLA 2 40000,00     0 ADD 2 40002,00
20005     0 ROV 0 40002,00     0 FUO 2 40004,00     0 TRA 0 20011,00     0 TRA 0 20016,00     0 CLS 2 40000,00
20012     0 ADD 2 40004,00     0 STD 0 40000,00     0 TRA 0 20020,00     0 TRA 0 20020,00     0 CAL 2 14376,00
20017     0 STL 0 40006,00     0 ICZ 2 40006,00     0 TRA 0 20023,00     0 TRA 0 20031,00     0 CLA 2 40004,00
20024     0 STD 0 72652,00     0 CLA 2 40002,00     0 STD 0 72650,00     0 TRM 0 10253,00     0 STD 0 40000,00
20031     0 CLA 2 40000,00     0 FLO 2 40002,00     0 OCA 0 00001,00     0 CAL 2 14376,00     0 STL 0 40007,00
20036     0 TRM 0 05300,00


      TIME USED:  00:00:14     PAGES USED:    3               19:18:50
```

1. This causes the code to be printed as it is compiled.
2. Causes the routine number and LEFT1-LEFT5 and RIGHT1-RIGHT3 to be printed.
3. EXEC 12 ↓ is called to add -X and ZEBRA, it knows to subract X because of ④
4. The neration is bit set in LEFT4.

```
##########################################################################################################
OPERAIOR-040 14 MAY 64  19:11:05  MAGIC  PAGES:  50  TIME:   1                          CC35.013     J. FELDMAN
                                                                                                   COMPUTER CENT:R

                                                         00:00:04

CO                     EXAMPLE 3
SN        DUMP
                     BEGIN
       BEGIN REAL X,Y, ZEDD; BOOLEAN P,Q,ZEDE;
       ZEDE ← IF X/Y+ZEDD-X = X THEN P ELSE Q;
           X ← X*X + X*X END
                     ;
      BEGIN REAL X, Y, Z; BOOLEAN P,Q;
         X ← Y + X*X*Z; (3)
       X ←  I↑I; Y ← 1.5; Z ← X/3;
(1)FAULT    1
FAULT       1
      P ← TRUE;  Q ← FALSE      ;
       P ← Q END
         END
20000     0 CLA 2 40000,00     0 DIV 2 40002,00     0 ADD 2 40004,00     0 SUB 2 40000,00     0 FUO 2 40000,00
20005     0 TRA 0 20011,00     0 CAL 2 40006,00     0 STL 0 72400,77     0 TRA 0 20013,00     0 CAL 2 40007,00
20012     0 STL 0 72400,77     0 CAL 2 72400,77     0 STL 0 40010,00     0 CLA 2 40000,00     0 MPY 2 40000,00
20017     0 STD 0 72401,77     0 CLA 2 40000,00     0 MPY 2 40000,00     0 ADD 2 72401,77     0 STD 0 40000,00
20024     0 CLA 2 40011,00     0 MPY 2 40011,00     0 MPY 2 40015,00     0 ADD 2 40013,00     0 STD 0 40011,00
20031 (2) 0 CAL 0 00271,00     0 STD 0 72652,00 (2) 0 CAL 0 00271,00     0 STD 0 72650,00     0 TRM 0 10253,00
20036     0 STD 0 40011,00     0 CLA 2 14401,00     0 STD 0 40013,00     0 CLA 2 40011,00     0 DIV 0 00003,00
20043     0 STD 0 40015,00     0 CAL 2 14377,00(4)  0 STL 0 40017,00     0 CAL 2 14376,00(4)  0 STL 0 40020,00
20050     0 CAL 0 40020,00     0 STL 0 40017,00     0 TRM 0 05300,00


          TIME USED:  00:00:08    PAGES USED:    1               19:11:12
```

1. The semantic error message FAULT 1 is printed twice because 'I' was not declared.

2. Since OK was not set FALSE, translation continues using the internal name of 'I' as its semantics.

3. The floating point constant '1.5' is put in a cell in the constant region.

4. TRUE and FALSE are also absolute constants.

Bibliography

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2. Brooker, R. and D. Morris, "An Assembly Program for a Phrase Structure Language". Computer Journal Vol. 3 p. 168 (1960).

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Errata Sheet

This is an errata sheet for the paper entitled, "A Formal Semantics for Computer Oriented Languages", by Jerome A. Feldman, Computation Center, Carnegie Institute of Technology.

Page	Line(s)	Correction
vi	12	Should read: ...as a computer system.
3	* 3	Should read: ...theorems in the propositional calculus
24	3, 7	K should be k
25	8 8	
63	* 3	Should read: ...exponentiation which is actually...
67	11	Should read: ...computed before being...
84	8	Should read: ...Besides, we felt...
95	13	Should read: ...share the same...
98	12	Should read: ...students as instructors
96	12	Should read: ...was devoted to progress
103	9	Should read: ...making [illegible] the optional
112	2nd operation	Should read: OCS [illegible] → (35)

* Number of line, counting from the bottom of the page

The author's address is now:

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APPENDICES

Notes on the Appendices

The material contained in these appendices forms an integral part of the thesis. The basis for most of them is one or more machine listings. In all cases these are actual runs of the programs being described.

Appendices A-C comprise a complete description of the subset of ALGOL 60 which we call the small language. The BNF syntax of the small language which is Appendix A is what might be given in a published paper on the small language. The Appendices B and C are a solution to the problem of building a compiler for the small language.

Appendix B contains a run of the production loader on the syntax of the small language. The results of this run are some tightly packed tables which will control the scanning of small language source programs. The notation used in these tables is described in that section.

Appendix C contains a run of the semantic loader on the FSL semantics of the small language. The tables produced there are actually short programs which will be executed by the Basic Compiler. We will give a capsule description of the G-20 machine code at the end of these notes. This description will also be of use in reading Appendix F, which contains the translations of sample programs in the small language.

Appendices D and E describe the semantic meta-language, FSL. The Backus Normal Form syntax constitutes Appendix D while the Production Language Syntax is Appendix E. The tables produced in Appendix E follow the same format as those for the productions of the small language (Appendix B).

In order to fully understand the appendices, one must have some knowledge of G-20 machine code. We will present a brief description of the machine, emphasizing its differences from the better known computers of its class.

The Control Data (neé Bendix) G-20 at Carnegie Tech is a large single address machine. Among its more interesting features are a floating point accumulator and a special operand assembly (OA) register. These are the only hardware registers with which we will be concerned. Although the G-20 has 64 index registers, these are in its 6 μ-second core memory and thus have appreciable access times. We will describe the G-20 command structure as it will appear in Appendices C and F. The format of a command is:

f xxx m ddddd , ii

whre 'f' denotes the interrupt flag (0-3) used by the machine hardware. The symbols 'xxx' denote one of the 3-letter mnemonic opcodes which we will describe below. The 'm' denotes the addressing mode (0-3) and will also be described below. The field marked 'ddddd' stands for the five digit octal address used in a G-20 command and the 'ii' denotes one of the octal 100 index registers (0-77). The internal representation of a command is slightly different than our picture.

Before describing the commands, we must say something about the address structure of the G-20. This is based on the use of the OA register which automatically combines with the address field of every command according to the mode specified in the command. If we represent the address field of a command by A, the index field by I and the contents of OA register as (OA) we attain the following rules for building X, the effective address.

Mode	Effective Address
0	$(OA) + A + (I) = X$
1	$(OA) + (A) + (I) = X$
2	$((OA) + A + (I)) = X$
3	$((OA) + (A) + (I)) = X$

The normal mode for stores and transfer commands is mode 0, while all other commands are normally in mode 2. There are special commands for operating on the OA and, except for these instructions, the OA is set to zero after every command.

In the table of opcodes (Figure 4), (ACC) stands for the accumulator and all the symbols defined above retain their meanings. Notice that for all conditional statements the next command is executed if the

Partial List of G-20 Opcodes

Address Preparation

OCA	$X \rightarrow (OA)$
OCA	$-X \rightarrow (OA)$
OAD	$(ACC) + X \rightarrow (OA)$
OSU	$(ACC) - X \rightarrow (OA)$

Add and Substract

CLA	$X \rightarrow (ACC)$
CLS	$-X \rightarrow (ACC)$
ADD	$(ACC) + X \rightarrow (ACC)$
SUB	$(ACC) - X \rightarrow (ACC)$
ADN	$- (ACC) - X \rightarrow (ACC)$
SUN	$- (ACC) + X \rightarrow (ACC)$
ADA	$(ACC) + X \rightarrow (ACC)$
SUA	$(ACC) - X \rightarrow (ACC)$

Arithmetic Tests

FOM	$X < 0$
FOP	$X > 0$
FLO	$(ACC) < X$
FGO	$(ACC) > X$

Multiply and Divide

MPY	$(ACC) * X \rightarrow (ACC)$
DIV	$(ACC) / X \rightarrow (ACC)$
RDV	$X / (ACC) \rightarrow (ACC)$

Logic Operations

CAL	$X \quad (ACC)$
CCL	$X \quad (ACC)$
ADL	$(ACC) + X \rightarrow (ACC)$
SUL	$(ACC) - X \rightarrow (ACC)$
EXL	$(ACC) \wedge X \rightarrow (ACC)$
UNL	$(ACC) \vee X \rightarrow (ACC)$

Logic Tests

IOZ	$X = 0$
IOZ	$X = 0$
IUO	$(ACC) - X \neq 0$

Store

STL	$(ACC) \rightarrow X$
STD	$(ACC) \rightarrow X$
STI	$(ACC) \rightarrow X$
STZ	$0 \rightarrow X$

Index Register Codes

LXP	$X \rightarrow I$	
LXM	$-X \rightarrow I$	
ADX	$(I) + X \rightarrow I$	
SUX	$(I) - X \rightarrow I$	
AXT	$(I) + X \rightarrow I$	$(=0?)$
SXT	$(I) - X \rightarrow I$	$(=0?)$

Transfer of Control

TRA	$X \rightarrow NC$
TRM	$(NC) \rightarrow X; X + 1 \rightarrow NC$

Figure 4.

condition holds. With this capsule view of the G-20 and the descriptions accompanying the examples, it should be possible to follow the code generated in Appendices C and F. A much more complete set of examples, including a number of source languages, will appear as a separate paper.

Appendix A

Syntax of a Small Language

```
<arithmetic expression> :: =  <term> | ±  <term> |
                                <arithmetic expression>  ±  <term>

<term>  :: =  <factor> | <term> */ <factor>

<factor>  :: =  <primary> | <factor> ↑ <primary>

<primary>  :: =  <identifier> | (<arithmetic expression>)

<simple boolean>  :: =  <identifier> | <arithmetic expression>
                          <relation>  <arithmetic expression>

<boolean>  :: =  <simple boolean> | <if clause> <simple boolean>
                   ELSE  <boolean>

<if clause>  :: =  IF <boolean> THEN

<if statement>  :: =  <if clause>  <unconditional>

<assignment>  :: =  <identifier> ← <arithmetic expression> |
                      <identifier> ← <boolean>

<go to statement>  :: =  GO TO <identifier>

<conditional>  :: =  <if statement> | <if statement>  ELSE <statement>

<unconditional>  :: =  <assignment> | <go to statement> | <block>

<declaration>  :: =  <type>  <type list> | <declaration> ; <type>
                       <type list>

<type>  :: =  REAL | BOOLEAN | LABEL

<type list>  :: =  <identifier> | <type list> , <identifier>

<head>  :: =  BEGIN | BEGIN <declaration> | <head> ; <statement>

<block>  :: =  <head>  END

<statement>  :: =  <conditional> | <unconditional> | <empty> |
                     <identifier> : <statement>
```

Notes on Appendix B

The appendix is a machine run of the Production Language syntax of the small language. Besides the productions themselves there are three tables given as input to the Production Loader. The first is a table of reserved identifiers, both those used internally and those which appear in the source code. The second table defines the class names (metacharacters) as discussed in Chapter II. The table of actions contains all those mentioned in Chapter II as well as others used internally by the system.

As we have mentioned, the tables built by the Production Loader are tightly packed and thus difficult to read. The small table at 37715 to 40011 contains initializing information for the Basic Compiler. The two tables (other stuff and LABELS) before the production table contain debugging information which will not concern us here.

To read the production table we must understand the internal numbering system for symbols. Reserved symbols are given octal integers starting at 200 as internal names. After the last number assigned to a reserved symbol (261 for the small language), the source code identifiers are numbered sequentially.

The production table consists of two types of words, head cells and operands. Consider the first entry (62245) in the production table.

```
0  105  02  10000
```

The '105' marks this as the head cell of a production and the '02' gives the relative address of the next head cell. The '10000' is the relative address of the interpretation table entry corresponding to this production. We will discuss the interpretation table below.

The next cell contains '252' in the low order positions. This is the octal integer which corresponds to 'BEGIN'. A word of all zeros in the production table corresponds to a ' ∅ ' in a production.

The interpretation table is easier to follow. The integer in the high order position represents one of the actions in the Action Table. These are numbered sequentially starting with '1' for EXEC. The parameter to the action is contained in the low order bits of the same word. These tables are interpreted by the Basic Compiler in recognizing source language text.

Appendix B

Productions for the Small Language

```
*        SYMBOLS
*         12 INTERNAL SYMBOLS
                           I
                           P
                           F
                           T
                           E
                           SBE
                           BE
                           ICL
                           UN
                           S
                           HEAD
                           |→
     +                     +
     -                     -
     *                     *
     /                     /
     =                     =
     v                     v
     ≠                     ≠
     ^                     ^
     <                     <
     >                     >
     ¬<                    ¬<
     ¬>                    ¬>
     ¬                     ¬
     ↑                     ↑
     ↓                     ↓
     .                     .
     ,                     ,
     ;                     ;
     :                     :
     ←                     ←
     →                     →
     $                     $
     (                     (
     [                     [
     ]                     ]
     )                     )
     REAL                  REAL
     BOOLEAN               BOOL
     LABEL                 LABL
     BEGIN                 BEGN
     END                   END
     GOTO                  GO
     IF                    IF
     THEN                  THEN
     ELSE                  ELSE
     TRUE                  TRUE
     FALSE                 FALS
*        METACHARACTERS
```

```
M <OP> + - * / ↑
M <TP> REAL BOOL LABL
M <RLP> = ≠ < > ¬< ¬>
M <PM> + -
M <TD> * /
*        ACTIONS

    EXEC
    NSTK
    STAK
    VALU
    SUBR
    SCAN
    NEXT
    GET
    BOOK
    RETURN
    ERROR
    HALT
    CON
    NUM
    FOUT
    STRIN
*        PRODUCTIONS
37715    00000000074  00053117163  00003754224  00001020101  00003720323  00000000523  00001336065  00000016307
37725    00017232775  00125776240  20000034000  01177202242  00003402170  00000000073  00000000072  00000000071
37735    00000000070  00000000065  00000000035  00000000034  00000000076  00000000067  00000000037  00000000053
37745    00000000074  00000000075  00000000036  00000000036  00000000036  00000000066  00000000064  00000000063
37755    00000000062  00000000061  00000000060  00000000057  00000000056  00000000055  00000000054  30000000000
37765    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37775    30000000000  30000000000  30000000000  00000000261  30000000000  02000000046  00000000032  00000000014
40005    30000000000  02000000062  00000000213  30000000000  30000000000
...
```

```
S0                        BEGN  |                        |  EXEC 1      *D1
                          <SG>  |                        |  ERROR 0     Q1
D1                        <TP>  |                        |  SCAN        *D2
                    BEGN  END   | →              S      |              *S1
                    BEGN  ;     | →              BEGN   |              *D1
              BEGN  |→    <SG>  | → HEAD ;       <SG>   |  EXEC 2      S1
                    BEGN  <SG>  | → HEAD ;       <SG>   |  EXEC 2      S1
D2            REAL  I     <SG>  |                        |  EXEC 4      D3
              BOOL  I     <SG>  |                        |  EXEC 5      D3
              LABL  I     <SG>  |                        |  EXEC 30     D3
D3            <TP>  I     ,     | →              <TP>   |  SCAN        *D2
        |→    <TP>  I     ;     | →              |→     |              *D1
              <TP>  I     ;     | →              |→     |              *D1
                          <SG>  |                        |  ERROR 1     Q1
S1                        BEGN  |                        |              *D1
                          IF    |                        |              *B1
                          GO    |                        |              *G1
                          ;     | →       S      ;      |              S9
                          END   |                        |              S9
                          I     |                        |              *S2
S2                  I     :     | →                      |  EXEC 26     *S1
                    I     ←     |                        |              *EX1
                          <SG>  |                        |  ERROR 2     Q1
I1                  ←     ICL   |                        |              *B1
                    IF    ICL   |                        |              *B1
              SBE   ELSE  ICL   |                        |              *B1
                          ICL   |                        |  EXEC 3      *S1
                          <SG>  |                        |  ERROR 4     Q1
UN1           ICL   UN    <SG>  |                        |              C1
                    UN    <SG>  | →       S      <SG>   |              S9
                          <SG>  |                        |  ERROR 5     Q1
C1            ICL   UN    ELSE  |                        |  EXEC 6      *S1
              ICL   UN    <SG>  | →       S      <SG>   |  EXEC 7      S9
                          <SG>  |                        |  ERROR 6     Q1
P1                        I     | →              P      |  EXEC 9      *F1
                          (     |                        |              *P1
                          +     | →                      |              *P1
                          -     |                        |              *P1
                          <SG>  |                        |  ERROR 7     Q1
F1      F     ↑     P     <SG>  | →       F      <SG>   |  EXEC 28     F2
                    P     <SG>  | →       F      <SG>   |              F2
F2                  F     ↑     |                        |              *P1
T1      T     *     F     <SG>  | →       T      <SG>   |  EXEC 10     T2
        T     /     F     <SG>  | →       T      <SG>   |  EXEC 11     T2
                    F     <SG>  | →       T      <SG>   |              T2
T2                  T     <TD>  |                        |              *P1
E1      E     +     T     <SG>  | →       E      <SG>   |  EXEC 12     E2
        E     -     T     <SG>  | →       E      <SG>   |  EXEC 13     E2
              -     T     <SG>  | →       E      <SG>   |  EXEC 14     E2
                    T     <SG>  | →       E      <SG>   |              E2
E2                  E     <PM>  |                        |              *P1
              (     E     )     | →              P      |  EXEC 15     *F1
                    E     <RL>  |                        |              *P1
        I     ←     E     <SG>  | →       UN     <SG>   |  EXEC 16     UN1
        E     =     E     <SG>  | →       SBE    <SG>   |  EXEC 17     B2
```

```
           E     <     E     <SG>  | →   SBE   <SG>  |    EXEC 18    B2
           E     >-    E     <SG>  | →   SBE   <SG>  |    EXEC 19    B2
           E     <RL>  E     <SG>  | →   SBE   <SG>  |    EXEC 17    B2
                             <SG>  |                 |    ERROR 8    Q1
B1                           IF    |                 |               *B1
                             +     | →               |               *P1
                             -     |                 |               *P1
                             (     |                 |               *P1
B4                     I     <OP>  | →   P     <OP>  |    EXEC 8     F1
                       I     <RL>  | →   E     <RL>  |    EXEC 8     *P1
                       I     <SG>  | →   SBE   <SG>  |    EXEC 20    B2
                             I     |                 |               *B4
B2                     SBE   ELSE  |                 |               *B1
                       SBE   <SG>  | →   BE    <SG>  |               B3
B3               IF    BE    THEN  | →         ICL   |    EXEC 21    I1
     ICL   SBE   ELSE  BE    <SG>  | →   BE    <SG>  |    EXEC 22    B3
           I     ←     BE    <SG>  | →   UN    <SG>  |    EXEC 23    UN1
EX1                          I     |                 |               *EX2
                             IF    |                 |               *B1
                             +     | →               |               *P1
                             -     |                 |               *P1
                             (     |                 |               *P1
EX2                    I     <OP>  | →   P     <OP>  |    EXEC 8     F1
                       I     <RL>  | →   E     <RL>  |    EXEC 8     *P1
           I     ←     I     <SG>  | →   UN    <SG>  |    EXEC 24    UN1
                             <SG>  |                 |    ERROR 8    Q1
G1                     GO    I     | →         UN    |    EXEC 25    *UN1
                             <SG>  |                 |    ERROR 9    Q1
S9   ICL   UN    ELSE  S     <SG>  | →   S     <SG>  |    EXEC 27    S9
     ICL   UN    ELSE  UN    <SG>  | →   S     <SG>  |    EXEC 27    S9
           HEAD  ;     S     ;     | →   HEAD  ;     |               *S1
           HEAD  ;     S     END   | →         UN    |    EXEC 29    ND1
ND1                    |→    UN    | →         |→    |    EXEC 31    Q1
                             <SG>  |                 |               *UN1
Q1                           <SG>  |                 |    HALT       Q1
*          END

OTHER STUFF
I 1          4
I 2          0
I 3          0
I 4          1
I 5          0
I 6         14
I 7         61
I 8         67
I 9          0
I10         56
I11         67
I12         12
I13         12
I14          5
I15          0
I16         26
```

```
 I17        2
 I18      293
 I19        0
 I20       28
 I21    16333
 J 0      287
 J 1        0
 J 2        1
 J 3       61
 J 4       67
 J 5        7
 J 6       51
 J 7       12
```

```
            LABEL TABLE

        LABEL NAME     VALUE
   1       S0              0
   2       D1              4
   3       Q1            285
   4       D2             19
   5       S1             46
   6       D3             31
   7       B1            190
   8       G1            253
   9       S9            258
  10       S2             58
  11       EX1           230
  12       I1             66
  13       UN1            80
  14       C1             89
  15       P1             99
  16       F1            109
  17       F2            117
  18       T1            120
  19       T2            133
  20       E1            136
  21       E2            153
  22       B2            209
  23       B4            198
  24       B3            215
  25       EX2           240
  26       ND1           280
  27                       1
```

```
           PRODUCTION TABLE
 62243   01050210000  00000000252  01050210003  00000000000  01050210005  01050300006  01050310010  00000000253
 62255   00000000252  01050310014  00000000235  00000000252  01050410017  00000000000  00000000213  00000000252
 62265   01050310025  00000000000  00000000252  01050410033  00000000000  00000000200  00000000246  01050410035
 62275   00000000000  00000000200  00000000250  01050410037  00000000000  00000000200  00000000251  01050410041
 62305   00000000234  00000000200  01050300006  01050510045  00000000235  00000000200  01050300006  00000000213
 62315   01050410050  00000000235  00000000200  01050300006  01050210054  00000000000  01050210056  00000000252
 62325   01050210060  00000000255  01050210062  00000000254  01050210064  00000000235  01050210070  00000000253
 62335   01050210071  00000000200  01050310073  00000000236  00000000200  01050310077  00000000237  00000000200
```

```
62345   01050210101 00000000000 01050310103 00000000207 00000000237 01050310105 00000000207 00000000255
62355   01050410107 00000000207 00000000257 00000000205 01050210111 00000000207 01050210114 00000000000
62365   01050410116 00000000000 00000000210 00000000207 01050310117 00000000000 00000000210 01050210123
62375   00000000000 01050410125 00000000257 00000000210 00000000207 01050410130 00000000000 00000000210
62405   00000000207 01050210135 00000000000 01050210137 00000000200 01050210144 00000000242 01050210146
62415   00000000214 01050210151 00000000215 01050210153 00000000000 01050510155 00000000000 00000000201
62425   00000000231 00000000202 01050310161 00000000000 00000000201 01050310165 00000000231 00000000202
62435   01050510167 00000000000 00000000202 00000000216 00000000203 01050510173 00000000000 00000000202
62445   00000000217 00000000203 01050310177 00000000000 00000000202 01050310203 01050200021 00000000203
62455   01050510205 00000000000 00000000203 00000000214 00000000204 01050510211 00000000000 00000000203
62465   00000000215 00000000204 01050410215 00000000000 00000000203 00000000215 01050310222 00000000000
62475   00000000203 01050310226 01050200017 00000000204 01050410230 00000000245 00000000204 00000000242
62505   01050310235 01050600011 00000000204 01050510237 00000000000 00000000204 00000000237 00000000200
62515   01050510244 00000000000 00000000204 00000000220 00000000204 01050510251 00000000000 00000000204
62525   00000000224 00000000204 01050510256 00000000000 00000000204 00000000225 00000000204 01050510263
62535   00000000000 00000000204 01050600011 00000000204 01050210270 00000000000 01050210272 00000000255
62545   01050210274 00000000214 01050210277 00000000215 01050210301 00000000242 01050310303 01050500001
62555   00000000200 01050310310 01050600011 00000000200 01050310316 00000000000 00000000200 01050210323
62565   00000000200 01050310325 00000000257 00000000205 01050310327 00000000000 00000000205 01050410333
62575   00000000256 00000000206 00000000255 01050610337 00000000000 00000000206 00000000257 00000000205
62605   00000000207 01050510344 00000000000 00000000206 00000000237 00000000200 01050210351 00000000200
62615   01050210353 00000000255 01050210355 00000000214 01050210360 00000000215 01050210362 00000000242
62625   01050310364 01050500001 00000000200 01050310371 01050600011 00000000200 01050510377 00000000000
62635   00000000200 00000000237 00000000200 01050210404 00000000000 01050310406 00000000200 00000000254
62645   01050210413 00000000000 01050610415 00000000000 00000000211 00000000257 00000000210 00000000207
62655   01050610422 00000000000 00000000210 00000000257 00000000210 00000000207 01050510427 00000000235
62665   00000000211 00000000235 00000000212 01050510432 00000000253 00000000211 00000000235 00000000212
62675   01050310436 00000000210 00000000213 01050210441 00000000000 01050210443 00000000000 30000000000

          AUXILIARY PRODUCTION TABLE
65202   00000000000 00000000210 00000000213 00000000253 00000000210 00000000235 00000000000 30000000000
65212   30000000000 30000000000 30000000000 30000000000 30000000000 30000000000 30000000000 30000000000
65222   30000000000 30000000000 30000000000 30000000000

          INTERPRETATION TABLE
65227   00010000001 00060000001 00070000004 00130000000 00070000435 00060000000 00060000001 00070000023
65237   00020000002 00030000211 00060000001 00070000056 00020000001 00060000001 00070000004 00020000003
65247   00030000212 00030000235 00030000000 00010000002 00070000056 00020000002 00030000212 00030000235
65257   00030000000 00010000002 00070000056 00010000004 00070000037 00010000005 00070000037 00010000036
65267   00070000037 00020000002 00060000000 00060000001 00070000023 00020000003 00060000001 00070000004
65277   00020000003 00030000213 00060000001 00070000004 00130000001 00070000435 00060000001 00070000004
65307   00060000001 00070000276 00060000001 00070000375 00020000001 00030000211 00030000000 00070000402
65317   00070000402 00060000001 00070000072 00020000002 00010000032 00060000001 00070000056 00060000001
65327   00070000346 00130000002 00070000435 00060000001 00070000276 00060000001 00070000276 00060000001
65337   00070000276 00010000003 00060000001 00070000056 00130000004 00070000435 00070000131 00020000002
65347   00030000211 00030000000 00070000402 00130000005 00070000435 00010000006 00060000001 00070000056
65357   00020000003 00030000211 00030000000 00010000007 00070000402 00130000006 00070000435 00020000001
65367   00030000201 00010000011 00060000001 00070000155 00060000001 00070000143 00020000001 00060000001
65377   00070000143 00060000001 00070000143 00130000007 00070000435 00020000003 00030000000 00010000034
65407   00070000165 00020000002 00030000202 00030000000 00070000165 00060000001 00070000143 00020000003
65417   00030000000 00010000012 00070000205 00020000003 00030000000 00010000013 00070000205 00020000002
65427   00030000203 00030000000 00070000205 00060000001 00070000143 00020000003 00030000000 00010000014
65437   00070000231 00020000003 00030000000 00010000015 00070000231 00020000003 00030000204 00030000000
65447   00010000016 00070000231 00020000002 00030000204 00030000000 00070000231 00060000001 00070000143
65457   00020000003 00030000201 00010000017 00060000001 00070000155 00060000001 00070000143 00020000004
```

```
65467   00030000210  00030000000  00010000020  00070000120  00020000004  00030000205  00030000000  00010000021
65477   00070000321  00020000004  00030000205  00030000000  00010000022  00070000321  00020000004  00030000205
65507   00030000000  00010000023  00070000321  00020000004  00030000205  00030000000  00010000021  00070000321
65517   00130000010  00070000435  00060000001  00070000276  00020000001  00060000001  00070000143  00060000001
65527   00070000143  00060000001  00070000143  00020000002  00030000201  00030000000  00010000010  00070000155
65537   00020000002  00030000204  00030000000  00010000010  00060000001  00070000143  00020000002  00030000205
65547   00030000000  00010000024  00070000321  00060000001  00070000306  00060000001  00070000276  00020000002
65557   00030000206  00030000000  00070000327  00020000003  00030000207  00010000025  00070000102  00020000005
65567   00030000001  00030000000  00010000026  00070000327  00020000004  00030000210  00030000000  00010000027
65577   00070000120  00060000001  00070000360  00060000001  00070000276  00020000001  00060000001  00070000143
65607   00060000001  00070000143  00060000001  00070000143  00020000002  00030000201  00030000000  00010000010
65617   00070000155  00020000002  00030000204  00030000000  00010000010  00060000001  00070000143  00020000004
65627   00030000210  00030000000  00010000030  00070000120  00130000010  00070000435  00020000002  00030000210
65637   00010000031  00060000001  00070000120  00130000011  00070000435  00020000005  00030000001  00030000000
65647   00010000033  00070000402  00020000005  00030000211  00030000000  00010000033  00070000402  00020000002
65657   00060000001  00070000056  00020000004  00030000210  00010000035  00070000430  00020000001  00010000037
65667   00070000435  00060000001  00070000120  00140000000  00070000435
•        TAPE 210
             RECORD TYPE                NUMBER OF RECORDS   STARTING RECORD

         SYMBOL TABLE                           1                 21 *+01
         HIERARCHY TABLE                        1                 21 *+01
         PRODUCTION TABLE                       1                 22 *+01
         METACHARACTER LISTS                    1                 22 *+01

        TIME USED!  00!02!43     PAGES USED!    8              19!14!09
```

Notes on Appendix C

This is a complete run of the semantics for the small language. All of the locations are in octal form and the meaning of the mnemonic opcodes is given at the beginning of the appendices. The semantic tables start at 65600 and extend to 66650. The table of addresses starting at 37000 is called the switching table. Each entry in this table is the first location of the code for a semantic routine. For example, the code for 12↓ (octal 14) starts at 66101 as described in cell 37014. The switching table is used by the compiler in executing semantic routines.

As an example we will consider the code generated for

12↓ CODE(VALUE2 ← LEFT4 + LEFT2) ↓

The first command increments a pointer because we are entering code brackets. The next four commands put LEFT4 (63337) and LEFT2 (63335) into the parameter regiorr. Then the generator for '+' is called by 'TRM 0 63405'. The next two commands set up and call the processor for 'VALUE2' which will adjust the compile time stack and put an accumulator symbol in RIGHT2. Finally, the semantic routine returns control to the basic compiler at 62110.

Tables and other storage for the translator start at 45777 and go down in memory. Addresses between 62000 and 65000 refer to routines in the basic compiler. Locations near 14400 are used for constants and any address below 10000 is in the monitor, except for the index registers 0-77.

```
≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠≠

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                                                       00:00:03




CO                                           APPENDIX C
CO                     FORMAL SEMANTICS OF THE SMALL LANGUAGE

SN        DUMP

   BEGIN TABLE SYMB[200,4] ; CELL LEV,T0,T1,T2,T3,T4,T5; STACK STR,SYM;
   TITLE REAL, BOOL, LABE; DATA LOGIC, INTEGER, SINGLE, DOUBLE;

   0↓  T3 ← TEMPLOC ↓

   1↓ LEV ← 0; STR ← STORLOC; SYM ← LOC[SYMB] ↓

   2↓ LEV ≠0 → PUSH[STR,STORLOC]; PUSH [SYM, LOC[SYMB]]$     ;
       TALLY[LEV] ↓

   3↓ PUSH[FLAD1,0]; CODE( ¬LEFT1 → JUMP[FLAD1]$) ↓


   4↓ T0← STORLOC; SET[T0,DOUBLE]; ENTER[ SYMB;LEFT2,T0,REAL,LEV];
      STORLOC ← STORLOC+2 ↓

   5↓ ENTER[SYMB;LEFT2,STORLOC,BOOL ,LEV];TALLY[STORLOC] ↓

   6↓ PUSH[FLAD2,0]; CODE( JUMP[FLAD2]); ASSIGN[FLAD1]↓

   7↓ ASSIGN[FLAD1]↓

   8↓ CONST[LEFT2]→ RIGHT2← LEFT2 :
      SYMB[LEFT2,,$,]= REAL→ RIGHT2← SYMB[LEFT2,$,,]:FAULT 1$$ ↓

   9↓ CONST[LEFT1] → RIGHT1 ← LEFT1 :
      SYMB[LEFT1,,$,]= REAL→ RIGHT1← SYMB[LEFT1,$,,]:FAULT 1$$ ↓

   10↓ CODE(VALUE2←LEFT4*LEFT2)↓

   11↓ CODE(VALUE2←LEFT4/LEFT2)↓

   12↓ CODE(VALUE2←LEFT4+LEFT2)↓

   13↓ CODE(VALUE2←LEFT4-LEFT2)↓

   14↓ CODE(VALUE2←-LEFT2)↓
```

```
15↓ RIGHT1←LEFT2↓

16↓ SYMB[LEFT4,,$,]=REAL→ COMT 2← SYMB[LEFT4,$,,];
    CODE(COMT 2← LEFT2) ; TEMPLOC ← T3 : FAULT 3$ ↓

17↓ CODE(VALUE2←LEFT4=LEFT2)↓

18↓ CODE(VALUE2←LEFT4<LEFT2)↓

19↓ CODE(VALUE2←LEFT4>LEFT2)↓

20↓CONST[LEFT2]→ RIGHT2← LEFT2 :
    SYMB[LEFT2,,$,]=BOOL→RIGHT2←SYMB[LEFT2,$,,];
  SET[RIGHT2,LOGIC] ; TEMPLOC ← T3 : FAULT 3$$↓

21↓ RIGHT1 ← LEFT2 ↓

22↓ CODE( LEFT5→ TEMPLOC← LEFT4:  TEMPLOC← LEFT2$) ;
    RIGHT2← TEMPLOC; SET[RIGHT2,LOGIC] ;
   TALLY[TEMPLOC] ↓

23↓ SYMB[LEFT4,,$,]=BOOL→ COMT 2← SYMB[LEFT4,$,,];
    CODE( COMT 2← LEFT2): FAULT 4$ ↓

24↓ COMT 4← SYMB[LEFT4,$,,];
   CONST[LEFT2] → COMT 2← LEFT2:
    SYMB[LEFT2,,$,]=SYMB[LEFT4,,$,] → COMT 2← SYMB[LEFT2,$,,]:
     FAULT 5 $ $; TEMPLOC ← T3;
   CODE( COMT 4← COMT 2) ↓

25↓ SYMB[LEFT1,,$,] ≠ LABE → FAULT 6:
     COMT 2← LOC[SYMB[LEFT1,$,,]];
   COMT 3← <COMT 2>; SYMB[LEFT1,,,$] ≠0 → CODE( JUMP[COMT 3]) :
   CODE( JUMP[CHAIN[ COMT 2] ]) $$ ↓

26↓ SYMB[LEFT2,,$,] ≠ LABE → FAULT 6:
         SYMB[0,,,$] ← 1 ;
   ASSIGN[LOC [ SYMB[ LEFT2,$,,]]] $↓

27↓ ASSIGN[FLAD2] ↓

28↓ CODE( VALUE2 ← LEFT4 ↑ LEFT2) ↓

29↓ MINUS[LEV]; POP[STR,STORLOC]; POP[SYM,LOC[SYMB]]  ↓

30↓ ENTER[SYMB;LEFT2,0,LABE, 0 ] ↓

31↓ CODE( STOP) ↓
```

SN TAPE 1

```
        END)
65600   0 CLA 0 00004,00   0 STI 0 45775,00   0 CLA 0 45774,00   0 STI 0 45777,00   0 CLA 0 00310,00
65605   0 STI 0 45776,00   0 LXP 0 44161,40   0 LXP 0 44015,41   0 CLA 0 00370,00   0 STL 0 44014,00
65612   0 CLA 0 00371,00   0 STL 0 44013,00   0 CLA 0 00372,00   0 STL 0 44012,00   0 CLA 2 00076,00
65617   0 STL 0 44327,00   0 TRA 0 17020,00   0 CLA 0 00000,00   0 STL 0 44333,00   0 CLA 2 00071,00
65624   0 STL 2 00040,00   0 CAL 2 45777,00   0 SIL 2 00041,00   0 TRA 0 62110,00   0 CAL 2 44333,00
65631   0 FUO 0 00000,00   0 TRA 0 65634,00   0 TRA 0 65643,00   0 LXM 0 00001,74   0 ADX 0 00001,40
65636   0 CLA 2 00071,00   0 STL 2 00040,00   0 ADX 0 00001,41   0 CAL 2 45777,00   0 STL 2 00041,00
65643   0 CAL 2 44333,00   0 ADD 0 00001,00   0 STL 0 44333,00   0 TRA 0 62110,00   0 ADX 0 00001,53
65650   0 CLA 0 00000,00   0 STL 2 00053,00   0 CAL 2 63334,00   0 STL 0 63347,00   0 TRM 0 63516,00
65655   0 CAL 2 63351,00   0 STL 0 63346,00   0 TRM 0 63664,00   0 LXM 0 00001,74   0 CAL 0 00053,00
65662   0 UNL 2 63251,00   0 STL 0 63346,00   0 TRM 0 64057,00   0 OCA 2 63365,77   0 CAL 2 00000,00
65667   0 UNL 2 00070,00   0 STL 2 63365,77   0 SUX 0 00001,77   0 LXM 0 00001,74   0 TRA 0 62110,00
656/4   0 CLA 2 00071,00   0 STL 0 44332,00   0 CAL 2 44332,00   0 UNL 2 63275,00   0 UNL 2 63313,00
65701   0 STL 0 44332,00   0 CAL 2 63335,00   0 STL 0 47022,00   0 CAL 2 44332,00   0 STL 0 47023,00
65706   0 CAL 2 44014,00   0 STL 0 47024,00   0 CAL 2 44333,00   0 STL 0 47025,00   0 CLA 0 45777,00
65713   0 TRM 0 64626,00   0 CLA 2 00071,00   0 ADD 0 00002,00   0 STI 0 00071,00   0 TRA 0 62110,00
65720   0 CAL 2 63335,00   0 STL 0 47022,00   0 CAL 2 00071,00   0 STL 0 47023,00   0 CAL 2 44013,00
65725   0 STL 0 47024,00   0 CAL 2 44333,00   0 STL 0 47025,00   0 CLA 0 45777,00   0 TRM 0 64626,00
65732   0 ADX 0 00001,71   0 TRA 0 62110,00   0 ADX 0 00001,54   0 CLA 0 00000,00   0 STL 2 00054,00
65737   0 CAL 0 00054,00   0 UNL 2 63251,00   0 STL 0 63346,00   0 TRM 0 64057,00   0 CAL 0 00053,00
65744   0 UNL 2 63251,00   0 TRM 0 64134,00   0 TRA 0 62110,00   0 CAL 0 00053,00   0 UNL 2 63251,00
65751   0 TRM 0 64134,00   0 TRA 0 62110,00   0 CAL 2 63335,00   0 IEZ 2 63225,00   0 OCS 0 00001,00
65756   0 CAL 2 14377,00   0 IUO 2 14377,00   0 TRA 0 65765,00   0 LXM 0 00001,74   0 CAL 2 63335,00
65763   0 STL 0 63342,00   0 TRA 0 66013,00   0 LXM 0 00001,74   0 LXP 0 00002,52   0 CAL 2 63335,00
657/0   0 STI 0 47034,00   0 CLA 0 45777,00   0 TRM 0 64570,00   0 CAL 3 47034,00   0 FUO 2 44014,00
657/5   0 TRA 0 66007,00   0 LXM 0 00001,74   0 LXP 0 00001,52   0 CAL 2 63335,00   0 STI 0 47034,00
66002   0 CLA 0 45777,00   0 TRM 0 64570,00   0 CAL 3 47034,00   0 STL 0 63342,00   0 TRA 0 66012,00
66007   0 LXM 0 00001,74   0 CLA 0 00001,00   0 TRM 0 64161,00   0 LXM 0 00001,74   0 LXM 0 00001,74
66014   0 TRA 0 62110,00   0 CAL 2 63334,00   0 IEZ 2 63225,00   0 OCS 0 00001,00   0 CAL 2 14377,00
66021   0 IUO 2 14377,00   0 TRA 0 66027,00   0 LXM 0 00001,74   0 CAL 2 63334,00   0 STL 0 63341,00
66026   0 TRA 0 66055,00   0 LXM 0 00001,74   0 LXP 0 00002,52   0 CAL 2 63334,00   0 STI 0 47034,00
66033   0 CLA 0 45777,00   0 TRM 0 64570,00   0 CAL 3 47034,00   0 FUO 2 44014,00   0 TRA 0 66051,00
66040   0 LXM 0 00001,74   0 LXP 0 00001,52   0 CAL 2 63334,00   0 STI 0 47034,00   0 CLA 0 45777,00
66045   0 TRM 0 64570,00   0 CAL 3 47034,00   0 STL 0 63341,00   0 TRA 0 66054,00   0 LXM 0 00001,74
66052   0 CLA 0 00001,00   0 TRM 0 64161,00   0 LXM 0 00001,74   0 LXM 0 00001,74   0 TRA 0 62110,00
66057   0 ADX 0 00001,74   0 CAL 2 63337,00   0 STL 0 63346,00   0 CAL 2 63335,00   0 STL 0 63347,00
66064   0 TRM 0 63455,00   0 LXP 0 00001,52   0 TRM 0 62472,00   0 TRA 0 62110,00   0 ADX 0 00001,74
660/1   0 CAL 2 63337,00   0 STL 0 63346,00   0 CAL 2 63335,00   0 STL 0 63347,00   0 TRM 0 63461,00
660/6   0 LXP 0 00001,52   0 TRM 0 62472,00   0 TRA 0 62110,00   0 ADX 0 00001,74   0 CAL 2 63337,00
66103   0 STL 0 63346,00   0 CAL 2 63335,00   0 STL 0 63347,00   0 TRM 0 63405,00   0 LXP 0 00001,52
66110   0 TRM 0 62472,00   0 TRA 0 62110,00   0 ADX 0 00001,74   0 CAL 2 63337,00   0 STL 0 63346,00
66115   0 CAL 2 63335,00   0 STL 0 63347,00   0 TRM 0 63411,00   0 LXP 0 00001,52   0 TRM 0 62472,00
66122   0 TRA 0 62110,00   0 CAL 2 63335,00   0 SIL 0 63347,00   0 TRM 0 63516,00   0 LXP 0 00001,52
66127   0 TRM 0 62472,00   0 TRA 0 62110,00   0 CAL 2 63335,00   0 STL 0 63341,00   0 TRA 0 62110,00
66134   0 LXP 0 00002,52   0 CAL 2 63337,00   0 SII 0 47034,00   0 CLA 0 45777,00   0 TRM 0 64570,00
66141   0 CAL 3 47034,00   0 FUO 2 44014,00   0 TRA 0 66166,00   0 LXM 0 00001,74   0 LXP 0 00001,52
66146   0 CAL 2 63337,00   0 STI 0 47034,00   0 CLA 0 45777,00   0 TRM 0 64570,00   0 CAL 3 47034,00
66153   0 STL 0 46465,00   0 ADX 0 00001,74   0 CAL 2 46465,00   0 STL 0 63346,00   0 CAL 2 63335,00
66160   0 STL 0 63347,00   0 TRM 0 63762,00   0 LXM 0 00001,74   0 CAL 2 44327,00   0 STI 0 00076,00
66165   0 TRA 0 66171,00   0 LXM 0 00001,74   0 CLA 0 00003.00   0 TRM 0 64161,00   0 LXM 0 00001,74
661/2   0 TRA 0 62110,00   0 ADX 0 00001,74   0 CAL 2 63337,00   0 STL 0 63346,00   0 CAL 2 63335,00
661/7   0 STL 0 63347,00   0 TRM 0 63527,00   0 LXP 0 00001,52   0 TRM 0 62472,00   0 TRA 0 62110,00
66204   0 ADX 0 00001,74   0 CAL 2 63337,00   0 STL 0 63346,00   0 CAL 2 63335,00   0 STL 0 63347,00
66211   0 TRM 0 63537,00   0 LXP 0 00001,52   0 TRM 0 62472,00   0 TRA 0 62110,00   0 ADX 0 00001,74
```

```
66216    0 CAL 2 63337,00    0 STL 0 63346,00    0 CAL 2 63335,00    0 STL 0 63347,00    0 TRM 0 63543,00
66223    0 LXP 0 00001,52    0 TRM 0 62472,00    0 TRA 0 62110,00    0 CAL 2 63335,00    0 IEZ 2 63225,00
66230    0 OCS 0 00001,00    0 CAL 2 14377,00    0 IUO 2 14377,00    0 TRA 0 66240,00    0 LXM 0 00001,74
66235    0 CAL 2 63335,00    0 STL 0 63342,00    0 TRA 0 66274,00    0 LXM 0 00001,74    0 LXP 0 00002,52
66242    0 CAL 2 63335,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00
66247    0 FUO 2 44013,00    0 TRA 0 66270,00    0 LXM 0 00001,74    0 LXP 0 00001,52    0 CAL 2 63335,00
66254    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00    0 STL 0 63342,00
66261    0 CAL 2 63342,00    0 UNL 2 63272,00    0 UNL 2 63313,00    0 STL 0 63342,00    0 CAL 2 44327,00
66266    0 STI 0 00076,00    0 TRA 0 66273,00    0 LXM 0 00001,74    0 CLA 0 00003,00    0 TRM 0 64161,00
662/3    0 LXM 0 00001,74    0 LXM 0 00001,74    0 TRA 0 62110,00    0 CAL 2 63335,00    0 STL 0 63341,00
66300    0 TRA 0 62110,00    0 CAL 2 63340,00    0 STL 0 63346,00    0 TRM 0 63664,00    0 LXM 0 00001,74
66305    0 ADX 0 00001,74    0 CAL 2 00076,00    0 STL 0 63346,00    0 CAL 2 63337,00    0 STL 0 63347,00
66312    0 TRM 0 63762,00    0 LXM 0 00001,74    0 TRM 0 63731,00    0 LXM 0 00001,74    0 ADX 0 00001,74
66317    0 CAL 2 00076,00    0 STL 0 63346,00    0 CAL 2 63335,00    0 STL 0 63347,00    0 TRM 0 63762,00
66324    0 LXM 0 00001,74    0 OCA 2 63365,77    0 CAL 2 00000,00    0 UNL 2 00070,00    0 STL 2 63365,77
66331    0 SUX 0 00001,77    0 LXM 0 00001,74    0 CLA 2 00076,00    0 STL 0 63342,00    0 CAL 2 63342,00
66336    0 UNL 2 63272,00    0 UNL 2 63313,00    0 STL 0 63342,00    0 ADX 0 00001,76    0 TRA 0 62110,00
66343    0 LXP 0 00002,52    0 CAL 2 63337,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00
66350    0 CAL 3 47034,00    0 FUO 2 44013,00    0 TRA 0 66373,00    0 LXM 0 00001,74    0 LXP 0 00001,52
66355    0 CAL 2 63337,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00
66362    0 STL 0 46465,00    0 ADX 0 00001,74    0 CAL 2 46465,00    0 STL 0 63346,00    0 CAL 2 63335,00
66367    0 STL 0 63347,00    0 TRM 0 63762,00    0 LXM 0 00001,74    0 TRA 0 66376,00    0 LXM 0 00001,74
663/4    0 CLA 0 00004,00    0 TRM 0 64161,00    0 LXM 0 00001,74    0 TRA 0 62110,00    0 LXP 0 00001,52
66401    0 CAL 2 63337,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00
66406    0 STL 0 46467,00    0 CAL 2 63335,00    0 IEZ 2 63225,00    0 OCS 0 00001,00    0 CAL 2 14377,00
66413    0 IUO 2 14377,00    0 TRA 0 66421,00    0 LXM 0 00001,74    0 CAL 2 63335,00    0 STL 0 46465,00
66420    0 TRA 0 66454,00    0 LXM 0 00001,74    0 LXP 0 00002,52    0 CAL 2 63335,00    0 STI 0 47034,00
66425    0 CLA 0 45777,00    0 TRM 0 64570,00    0 LXP 0 00002,52    0 CAL 2 63337,00    0 STI 0 47034,00
66432    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00    0 FUO 3 47034,00    0 TRA 0 66450,00
66437    0 L M 0 00001,74    0 LXP 0 00001,52    0 CAL 2 63335,00    0 STI 0 47034,00    0 CLA 0 45777,00
66444    0 TRM 0 64570,00    0 CAL 3 47034,00    0 STL 0 46465,00    0 TRA 0 66453,00    0 LXM 0 00001,74
66451    0 CLA 0 00005,00    0 TRM 0 64161,00    0 LXM 0 00001,74    0 LXM 0 00001,74    0 CAL 2 44327,00
66456    0 STI 0 00076,00    0 ADX 0 00001,74    0 CAL 2 46467,00    0 STL 0 63346,00    0 CAL 2 46465,00
66463    0 STL 0 63347,00    0 TRM 0 63762,00    0 LXM 0 00001,74    0 TRA 0 62110,00    0 LXP 0 00002,52
664/0    0 CAL 2 63334,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00
66475    0 FUO 2 44012,00    0 TRA 0 66500,00    0 TRA 0 66504,00    0 LXM 0 00001,74    0 CLA 0 00006,00
66502    0 TRM 0 64161,00    0 TRA 0 66543,00    0 LXM 0 00001,74    0 LXP 0 00001,52    0 CAL 2 63334,00
66507    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 2 47034,00    0 STL 0 46465,00
66514    0 CAL 3 46465,00    0 STL 0 46466,00    0 LXP 0 00003,52    0 CAL 2 63334,00    0 STI 0 47034,00
66521    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CAL 3 47034,00    0 FUO 0 00000,00    0 TRA 0 66527,00
66526    0 TRA 0 66534,00    0 LXM 0 00001,74    0 CAL 2 46466,00    0 STL 0 63346,00    0 TRM 0 64057,00
66533    0 TRA 0 66542,00    0 LXM 0 00001,74    0 CAL 2 46465,00    0 TRM 0 64126,00    0 CAL 2 63351,00
66540    0 STL 0 63346,00    0 TRM 0 64057,00    0 LXM 0 00001,74    0 LXM 0 00001,74    0 TRA 0 62110,00
66545    0 LXP 0 00002,52    0 CAL 2 63335,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00
66552    0 CAL 3 47034,00    0 FUO 2 44012,00    0 TRA 0 66556,00    0 TRA 0 66562,00    0 LXM 0 00001,74
66557    0 CLA 0 00006,00    0 TRM 0 64161,00    0 TRA 0 66601,00    0 LXM 0 00001,74    0 LXP 0 00003,52
66564    0 CLA 0 00000,00    0 STI 0 47034,00    0 CLA 0 45777,00    0 TRM 0 64570,00    0 CLA 0 00001,00
665/1    0 STL 2 47034,00    0 LXP 0 00001,52    0 CAL 2 63335,00    0 STI 0 47034,00    0 CLA 0 45777,00
665/6    0 TRM 0 64570,00    0 CAL 2 47034,00    0 TRM 0 64134,00    0 LXM 0 00001,74    0 TRA 0 62110,00
66603    0 CAL 0 00054,00    0 UNL 2 63251,00    0 TRM 0 64134,00    0 TRA 0 62110,00    0 ADX 0 00001,74
66610    0 CAL 2 63337,00    0 STL 0 63346,00    0 CAL 2 63335,00    0 STL 0 63347,00    0 TRM 0 64024,00
66615    0 LXP 0 00001,52    0 TRM 0 62472,00    0 TRA 0 62110,00    0 CAL 2 44333,00    0 SUB 0 00001,00
66622    0 STL 0 44333,00    0 CAL 3 00040,00    0 STI 0 00071,00    0 SUX 0 00001,40    0 CAL 3 00041,00
66627    0 STL 0 45777,00    0 SUX 0 00001,41    0 TRA 0 62110,00    0 CAL 2 63335,00    0 STL 0 47022,00
66634    0 CLA 0 00000,00    0 STL 0 47023,00    0 CAL 2 44012,00    0 STL 0 47024,00    0 CLA 0 00000,00
```

```
66641     0 STL 0 47025,00     0 CLA 0 45777,00     0 TRM 0 64626,00     0 TRA 0 62110,00     0 CLA 0 05300,00
66646     0 UNL 2 63166,00     0 TRM 0 64320,00     0 TRA 0 62110,00


37000    00000065616  00000065621  00000065630  00000065647  00000065674  00000065720  00000065734  00000065747
37010    00000065753  00000066015  00000066057  00000066070  00000066101  00000066112  00000066123  00000066131
37020    00000066134  00000066173  00000066204  00000066215  00000066226  00000066276  00000066301  00000066343
37030    00000066400  00000066467  00000066545  00000066603  00000066607  00000066620  00000066632  00000066645
37040    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37050    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37060    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37070    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37100    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37110    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37120    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37130    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37140    30000000000  30000000000  30000000000  30000000000

         TIME USED!  00!00!29    PAGES USED!    5            19!14!50
```

Appendix D

BNF Syntax of the Formal Semantic Language

```
<program head>  ::=  BEGIN  <declaration part> ; <sentence> |
                            <program head> ; <sentence

<semantic program>  ::=  <program head> END

<declaration part>  ::=  <declaration> | <declaration part> ;
                         <declaration>

<declaration>  ::=  <table dec> | <stack dec> | <cell dec> | <title dec> |
                    <data dec>

<table dec>  ::=  TABLE <table specifier> | RTABL <table specifier> |
                    <table dec> , <table specifier>

<stack dec>  ::=  STACK <identifier list> | RSTAK <identifier list>

<cell dec>  ::=  CELL <identifier list>

<title dec>  ::=  TITLE <identifier list>

<data dec>  ::=  DATA <identifier list>

<table specifier>  ::=  <table id>  [<integer> , <integer>]

<sentence>  ::=  <integer> ↓ <statement sequence> ↓

<statement sequence>  ::=  <statement> | <statement sequence> ;
                             <statement> | CODE (<statement sequence>)

<statement>  ::=  <unconditional> | <conditional> | '<label>'
                    <statement>

<unconditional>  ::=  <assignment> | <storage> | <transfer> |
                        <auxiliary> | CODE (<unconditional>)

<conditional>  ::=  <if clause>  <statement sequence> $ |
                    <if clause>  <statement sequence> :
                    <statement sequence> $ |  CODE (<conditional>)

<assignment>  ::=  <left side> ← <arithmetic> |
                   <left side> ← <boolean>
```

```
<left side>  :: =  <primary> | VALUE1 | VALUE2 | VALUE3

<storage>  :: =  <stack command> | <enter>

<stack command>  :: = PUSH [<stack id> , <arithmetic>] |
                      POP [<stack id> , <arithmetic>]

<enter>  :: =  ENTER [<table id> ; <expression list>]

<expression list>  :: =  <arithmetic> | <expression list> , <arithmetic>

<transfer>  :: =  JUMP [<arithmetic>] | MARKJUMP  [<arithmetic>] |
                  JUMP [<label>] | MARKJUMP [<subroutine>] |
                  EXECUTE [<arithmetic>]

<auxiliary>  :: =  SET [<arithmetic> , <data id>] |
                   FAULT <identifier> | TALLY [<arithmetic>]  |
                   MINUS [<arithmetic>] | ASSIGN [<arithmetic>] |  STOP

<operand>  :: = <<arithmetic>> | COMT␣<identifier> | RUNT␣<identifier> |
                <production operand> | <storage operand>

<production operand>  :: =  LEFT1 | LEFT2 | LEFT3 | LEFT4 | LEFT5 | RIGHT1 |
                            RIGHT2 | RIGHT3

<storage operand>  :: =  <table operand> | <cell id> | <stack id> |
                         <title id>

<table operand>  :: =  <table id> [<arithmetic> <commas> $ <commas>]

<commas>  :: =  , | <commas> , | <empty>

<primary>  :: =  <operand> | <constant> | (<arithmetic>) | LOC[<table id>] |
                 LOC [<stack id>] |  <system cell> | <flad>

<system cell>  :: =  CODELOC | STORLOC | TEMPLOC

<factor>  :: =  <primary> | <factor> ↑ <primary>

<term>  :: =  <factor> | <term>  < */ > <factor>

<arithmetic>  :: =  <term> | < ± > <term> | <arithmetic> < ± > <term> |
                    INT [<arithmetic>] | ABS [<arithmetic>] |
                     LOC [<arithmetic>] | CHAIN [<arithmetic>]
```

```
<boolean primary> :: = <arithmetic> <relation> <arithmetic> |
                       <operand> | (<boolean>) | TRUE | FALSE | SIGNAL |
                       TEST [<arithmetic> , <data id>] |
                       CONST [<arithmetic>] | OK

<boolean factor> :: = <boolean primary> | ¬ <boolean primary>

<boolean term> :: = <boolean factor> | <boolean term> ∧ <boolean factor>

<boolean> :: = <boolean term> | <boolean> ∨ <boolean term>

<if clause> :: = <boolean> →

<stack id> :: = <identifier>

<data id> :: = <identifier>

<table id> :: = <identifier>

<cell id> :: = <identifier>

<title id> :: = <identifier>

<label> :: = <identifier>

<identifier> :: = <letter> | <identifier> <letter> | <identifier> <digit>

<identifier list> :: = <identifier> | <identifier list> , <identifier>

<subroutine> :: = SIN | COS | EXP | LOG | ARCTAN | SIGN |

<flad> :: = FLAD1 | FLAD2 | FLAD3 | FLAD4

<relation> :: = = | > | < | ≠
```

Appendix E

Productions for the Formal Semantic Language

```
*        SYMBOLS
*         18 INTERNAL SYMBOLS
                           I
                           OP
                           AP
                           AF
                           AT
                           AE
                           TL
                           LO
                           BP
                           BS
                           BF
                           BE
                           IC
                           UN
                           UQ
                           S
                           SQ
                           |→
      +                    +
      -                    -
      *                    *
      /                    /
      =                    =
      ≠                    ≠
      <                    <
      >                    >
      ¬                    ¬
      ∨                    ∨
      ∧                    ∧
      ↑                    ↑
      ↓                    ↓
      .                    .
      ,                    ,
      ;                    ;
      :                    :
      ←                    ←
      →                    →
      $                    $
      (                    (
      [                    [
      ]                    ]
      )                    )
      '                    '
      BEGIN                BEGN
      END                  END
      STOP                 STOP
      STACK                STAK
      CELL                 CELL
      TITLE                NAME
      TABLE                TABL
      DATA                 DATA
```

JUMP	TR
MARKJUMP	TM
EXECUTE	X
ENTER	E
PUSH	ST
POP	RS
CHAIN	CH
ASSIGN	UC
CODE	CD.
FAULT	FALT
TALLY	TAL
MINUS	MIN
SET	SET
TEST	TEST
INT	IN
LOC	L
CODELOC	A
STORLOC	W
TEMPLOC	TLOC
COMT	CT
RUNT	RT
VALUE1	V1
VALUE2	V2
VALUE3	V3
LEFT1	Y1
LEFT2	Y2
LEFT3	Y3
LEFT4	Y4
LEFT5	Y5
RIGHT1	Z1
RIGHT2	Z2
RIGHT3	Z3
FLAD1	FL1
FLAD2	FL2
FLAD3	FL3
FLAD4	FL4
SIGNAL	SIG
RSTAK	RSTK
RTABL	RTAB
CONST	CON
CLEAR	CLE
OK	OK
PLACE	PLAC
DEPTH	DEP
SAR	SAR
SIN	SIN
COS	COS
EXP	EXP
LN	LN
SQRT	SQRT
ARCTAN	ARC
SIGN	SIGN
TRUE	TRUE
FALSE	FALS

* METACHARACTERS

```
M  <TD>  * /
M  <PM> + -
M  <RL> = < > ≠
M  <EN> = < > ≠ ] ) ; . ↑ ↓
M  <BN> ^ v ¬
M  <TP> TABL STAK CELL NAME   DATA RSTK RTAB
M  <V> V1 V2 V3
M  <Y>  Y1 Y2 Y3 Y4 Y5
M  <Z> Z1 Z2 Z3
M  <FL> FL1 FL2 FL3 FL4
M <CO> TR TM TAL MIN X CH UC ST RS SET CON CLE
M  <EN> = <  > ≠ ]  ) ; $ ↑ ↓
M  <AR> + - * / * < >  ≠
M  <SR> SAR SIN COS EXP LN SQRT ARC SIGN
*        ACTIONS

    EXEC
    NSTK
    STAK
    VALU
    SUBR
    SCAN
    NEXT
    GET
    BOOK
    RETURN
    ERROR
    HALT
    CON
    NUM
    FOUT
    STRIN
*        PRODUCTION TABLE
37621    00000000170  00053117163  00003754224  00003560231  00611714205  00003606376  00000000712  00000017105
37631    00000011111  00000063366  00000062722  00035514621  00164555471  00000001066  00027626043  00030330167
37641    00204435745  00204355575  11743611142  00055161016  00055161015  00055161014  00055161013  11333155110
37651    11333155107  11333155106  00126625667  00126625666  00126625665  00126625664  00126625663  13305117277
37661    13305117276  13305117275  00003455761  00000521703  20000006000  12320674355  20000006000  12063765243
37671    20000006000  01605475232  00000041132  00000031073  00003711324  00000063150  00136603374  00217175262
37701    00053146640  00000521147  00624052521  00027000157  00000053713  00003150344  00046435212  20000012000
37711    02727146472  20001742000  06571415646  00002026340  00000617662  00217142444  00220652116  00000467034
37721    00213552372  00003616226  00000016307  00017232775  00000000077  00000000073  00000000072  00000000071
37731    00000000070  00000000065  00000000035  00000000034  00000000076  00000000067  00000000037  00000000053
37741    00000000074  00000000075  00000000063  00000000061  00000000036  00000000066  00000000064  00000000062
37751    00000000060  00000000057  00000000056  00000000055  00000000054  30000000000  30000000000  30000000000
37761    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
37771    30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  00000000355
40001    30000000000  02000000053  00000000031  00000000103  30000000000  02000000156  00000000221  30000000000
40011    30000000000
...
```

```
D0                          BEGN  |                      |  EXEC 1      *D1
                            <SG>  |                      |  ERROR 0     Q2
D1                          <TP>  |                      |  SCAN        *D2
                            ↓     |                      |              *S1
                            END   | →                    |  HALT        D1
                            I     | →                    |  EXEC 2      *D1
                            <SG>  |                      |  ERROR 1     Q2
D2              <TP>  I     ,     | →             <TP>   |  EXEC 3      D1
                <TP>  I     ;     | →                    |  EXEC 3      *D1
                            [     | →                    |  SCAN        *TA
                            <SG>  |                      |  ERROR 2     Q2
TA        TABL  I     I     ,     |                      |  SCAN        *TA1
TA1 I     I     ,     I     ]     | →                    |  EXEC 4      *TA2
TA2                   TABL  ,     | →             TABL   |              D1
                      TABL  ;     | →                    |              *D1
                      TABL  <SG>  | →             <SG>   |              D1
                            <SG>  |                      |  ERROR 3     Q2
S1                          <CO>  |                      |  SCAN        *AP1
                            E     |                      |  SCAN        *SP1
                            <V>   |                      |  SCAN        *EX1
                            CD.   |                      |  EXEC 5      *CD
                            FALT  |                      |              *F1
                            STOP  | →             UN     |  EXEC 57     *UN
                            '     |                      |  SCAN        *LAB
                            ;     | →                    |              *S1
                      I     ↓     | →                    |  ERROR 19    *S1
EX1                         ¬     |                      |              *EX1
                            OK    | →             BP     |  EXEC 6      *BS1
                            W     | →             OP     |  EXEC 15     *OP1
                            TLOC  | →             OP     |  EXEC 16     *OP1
                            SIG   | →             BP     |  EXEC 17     *BS1
                            TEST  |                      |  SCAN        *AP1
                            <SG>  |                      |              AP1
LAB             '     I     '     | →                    |  EXEC 7      *S1
OP1             <AR>  OP    <SG>  | → <AR>  AP    <SG>   |              AF1
                      OP    <BN>  | →       BP    <BN>   |              BS1
                      OP    <SG>  | →       AP    <SG>   |              AF1
                            <SG>  |                      |  ERROR 5     Q1
ID        L     [     I     ]     | →             OP     |  EXEC 58     *OP1
                [     I     ]     | → [     AE    ]      |  EXEC 8      AE3
                ←     I     <EN>  | → ←     AE    <EN>   |  EXEC 8      AE2
          TL    [     I     ,     | → TL    AE    ,      |  EXEC 9      T0
                      I     [     | →       TL    [      |  EXEC 10     *AP1
                      I     <SG>  | →       OP    <SG>   |  EXEC 11     OP1
                            <SG>  |                      |  ERROR 6     Q1
B1                    CT    I     | →             OP     |  EXEC 12     *OP1
                      RT    I     | →             OP     |  EXEC 13     *OP1
                            <SG>  |                      |  ERROR 7     Q1
CD                    CD.   (     | →             CD.    |              *S1
                            <SG>  |                      |  ERROR 4     Q1
AP1                         (     |                      |              *EX1
                            I     |                      |              *ID
                            <PM>  |                      |              *AP1
                            IN    |                      |  SCAN        *AP1
                            L     |                      |  SCAN        *AP1
```

```
                          CH    |                  |  SCAN        *AP1
                          CT    |                  |              *B1
                          RT    |                  |              *B1
                          A     | →          AP    |  EXEC 14     *AF1
                          W     | →          AP    |  EXEC 15     *AF1
                          TLOC  | →          AP    |  EXEC 16     *AF1
                          <CO>  |                  |  SCAN        *AP1
                          <SR>  | →          AE    |  EXEC 18     *AE3
                          <Y>   | →          OP    |  EXEC 19     *OP1
                          <Z>   | →          AP    |  EXEC 20     *AF1
                          <     |                  |              *AP1
                          PLAC  | →          AE    |  EXEC 49     *AE2
                          <FL>  | →          AP    |  EXEC 22     *AF1
                          DEP   | →          AP    |  EXEC 66     *AF1
                          <SG>  |                  |  ERROR 18    Q1
AF1     AF    ↑     AP    <SG>  | →     AF   <SG>  |  EXEC 21     AF2
                    AP    ←     |                  |              *EX1
                    AP    <SG>  | →     AF   <SG>  |              AF2
AF2                 AF    ↑     |                  |              *AP1
AT1     AT    <TD>  AF    <SG>  | →     AT   <SG>  |  EXEC 23     AT2
                    AF    <SG>  | →     AT   <SG>  |              AT2
AT2                 AT    <TD>  |                  |              *AP1
AE1     AE    <PM>  AT    <SG>  | →     AE   <SG>  |  EXEC 24     AE2
              +     AT    <SG>  | →     AE   <SG>  |              AE2
              -     AT    <SG>  | →     AE   <SG>  |  EXEC 25     AE2
                    AT    <SG>  | →     AE   <SG>  |              AE2
                          <SG>  |                  |  ERROR 8     Q1
AE2                 AE    <PM>  |                  |              *AP1
                    AE    )     |                  |              AE3
              <     AE    >     | →          OP    |  EXEC 26     *OP1
                    AE    <RL>  |                  |              *AP1
              (     AE    )     | →          AP    |  EXEC 27     *AF1
        TL    [     AE    ,     | → TL  AE   ,     |              T0
              [     AE    ,     | →          AE    |  EXEC 27     *AP1
        E     TL    AE    ,     | →     E    TL    |  EXEC 28     *EX1
        AE    <RL>  AE    <SG>  | →     BP   <SG>  |  EXEC 29     BS1
        AP    ←     AE    <SG>  | →     UN   <SG>  |  EXEC 30     UN
        <V>   ←     AE    <SG>  | →     UN   <SG>  |  EXEC 31     UN
                    AE    <SG>  | →     BP   <SG>  |              BS1
AE3     IN    [     AE    ]     | →          AE    |  EXEC 32     *AE2
        TR    [     AE    ]     | →          UN    |  EXEC 33     *UN
        TM    [     AE    ]     | →          UN    |  EXEC 34     *UN
        L     [     AE    ]     | →          AP    |  EXEC 35     *AF1
        X     [     AE    ]     | →          UN    |  EXEC 36     *UN
        TAL   [     AE    ]     | →          UN    |  EXEC 37     *UN
        MIN   [     AE    ]     | →          UN    |  EXEC 38     *UN
        CH    [     AE    ]     | →          AE    |  EXEC 39     *AE2
        UC    [     AE    ]     | →          UN    |  EXEC 40     *UN
        CON   [     AE    ]     | →          BP    |  EXEC 64     *BS1
        CLE   [     AE    ]     | →          UN    |  EXEC 65     *UN
        ST    AE    AE    ]     | →          UN    |  EXEC 41     *UN
        RS    AE    AE    ]     | →          UN    |  EXEC 42     *UN
        SET   AE    AE    ]     | →          UN    |  EXEC 54     *UN
        TEST  AE    AE    ]     | →          BP    |  EXEC 56     *BS1
        E     TL    AE    ]     | →          UN    |  EXEC 43     *UN
```

```
                            <SG>  |                  |  ERROR 9      Q1
BS1              ¬    BP    <SG>  | →   BS    <SG>   |  EXEC 44      BF1
                      BP    <SG>  | →   BS    <SG>   |               BF1
BF1       BF     ^    BS    <SG>  | →   BF    <SG>   |  EXEC 45      BF2
                      BS    <SG>  | →   BF    <SG>   |               BF2
BF2                   BF    ^     |                  |               *EX1
BE1       BE     v    BF    <SG>  | →   BE    <SG>   |  EXEC 46      BE2
                      BF    <SG>  | →   BE    <SG>   |               BE2
                            <SG>  |                  |  ERROR 10     Q1
BE2                   BE    v     |                  |               *EX1
                      BE    →     | →         IC     |  EXEC 47      *S1
                 (    BE    )     | →         BP     |  EXEC 48      *BS1
          <V>    ←    BE    <SG>  | →   UN    <SG>   |  EXEC 31      UN
          AP     ←    BE    <SG>  | →   UN    <SG>   |  EXEC 50      UN
                            <SG>  |                  |  ERROR 11     Q1
UN                    UN    <SG>  | →   S     <SG>   |               S9
                            <SG>  |                  |  ERROR 12     Q1
S9        SQ     ;    S     <SG>  | →   SQ    <SG>   |               SQ1
     IC   SQ     !    S     $     | →         S      |  EXEC 53      *S9
                 CD.  S     )     | →         S      |  EXEC 52      *S9
                      S     <SG>  | →   SQ    <SG>   |               SQ1
                            <SG>  |                  |  ERROR 13     Q1
SQ1  IC   SQ     !    SQ    $     | →         S      |  EXEC 53      *S9
                 CD.  SQ    )     | →         S      |  EXEC 52      *S9
                 ↓    SQ    ↓     | →                |  EXEC 59      *D1
                 IC   SQ    :     |                  |  EXEC 55      *S1
                 IC   SQ    $     | →         S      |  EXEC 51      *S9
                      SQ    ;     |                  |               *S1
                            <SG>  |                  |  ERROR 15     Q1
SP1              E    (     I     | →   E     TL     |  EXEC 63      *SP2
SP2                   TL    ;     | →         TL     |               *EX1
                            <SG>  |                  |  ERROR 16     Q1
T0               TL   AE    ,     | →   TL    AE     |  EXEC 60      *T0
                 TL   AE    $     | →         OP     |  EXEC 61      *T1
T1                          ,     | →                |               *T1
                            )     | →                |               *OP1
                            <SG>  |                  |  ERROR 17     Q1
Q1                          ↓     | →                |               *D1
                            END   |                  |  HALT         Q1
                            <SG>  | →                |               *Q1
Q2                          ↓     |                  |               D1
                            END   |                  |  HALT         Q1
                            <SG>  | →                |               *Q2
F1                    FALT  <SG>  | →         UN     |  EXEC 62      *UN
                            <SG>  |                  |  ERROR 20     Q1
*         END

OTHER STUFF
I 1            4
I 2            0
I 3            0
I 4            0
I 5            0
I 6           20
```

```
I 7          62
I 8          67
I 9           0
I10           1
I11          67
I12           6
I13          15
I14           3
I15           0
I16          36
I17           2
I18         565
I19     *       0
I20          28
I21       16273
J 0         492
J 1           0
J 2           1
J 3          65
J 4          67
J 5           3
J 6          51
J 7          18


               LABEL TABLE

           LABEL NAME      VALUE
   1          D0               0
   2          D1               4
   3          Q2             481
   4          D2              14
   5          S1              48
   6          TA              26
   7          TA1             31
   8          TA2             37
   9          AP1            136
  10          SP1            452
  11          EX1             67
  12          CD             131
  13          F1             487
  14          UN             400
  15          LAB             81
  16          BS1            350
  17          OP1             85
  18          AF1            176
  19          Q1             475
  20          ID              97
  21          AE3            268
  22          AE2            219
  23          T0             461
  24          B1             123
  25          AF2            187
  26          AT1            190
  27          AT2            198
```

```
28        AE1        201
29        BF1        357
30        BF2        365
31        BE1        368
32        BE2        378
33        S9         405
34        SQ1        425
35        SP2        456
36        T1         469
37                     1

          PRODUCTION TABLE
62245   01050210000  00000000253  01050210003  00000000000  01050210005  01050700026  01050210010  00000000236
62255   01050210012  00000000254  01050210015  00000000200  01050210021  00000000000  01050410023  00000000240
62265   00000000200  01050700026  01050410026  00000000241  00000000200  01050700026  01050210032  00000000247
622/5   01050210036  00000000000  01050510040  00000000240  00000000200  00000000200  00000000261  01050610043
62305   00000000250  00000000200  00000000240  00000000200  00000000200  01050310047  00000000240  00000000261
62315   01050310051  00000000241  00000000261  01050310054  00000000000  00000000261  01050210057  00000000000
62325   01050210061  01051400054  01050210064  00000000270  01050210067  01050300035  01050210072  00000000275
62335   01050210075  00000000276  01050210077  00000000255  01050210104  00000000252  01050210107  00000000241
62345   01050310112  00000000236  00000000200  01050210116  00000000232  01050210120  00000000341  01050210125
62355   00000000310  01050210132  00000000312  01050210137  00000000334  01050210144  00000000302  01050210147
62365   00000000000  01050410150  00000000252  00000000200  00000000252  01050410154  00000000000  00000000201
623/5   01051000102  01050310160  01050300023  00000000201  01050310164  00000000000  00000000201  01050210170
62405   00000000000  01050510172  00000000250  00000000200  00000000247  00000000304  01050410177  00000000250
62415   00000000200  00000000247  01050410204  01051200011  00000000200  00000000243  01050510211  00000000240
62425   00000000200  00000000247  00000000206  01050310216  00000000247  00000000200  01050310224  00000000000
62435   00000000200  01050210231  00000000000  01050310233  00000000200  00000000313  01050310240  00000000200
62445   00000000314  01050210245  00000000000  01050310247  00000000246  00000000275  01050210252  00000000000
62455   01050210254  00000000246  01050210256  00000000200  01050210260  01050200003  01050210262  00000000303
62465   01050210265  00000000304  01050210270  00000000273  01050210273  00000000313  01050210275  00000000314
624/5   01050210277  00000000306  01050210304  00000000310  01050210311  00000000312  01050210316  01051400054
62505   01050210321  01051000112  01050210326  01050500040  01050210333  01050300045  01050210340  00000000230
62515   01050210342  00000000342  01050210347  01050400050  01050210354  00000000343  01050210361  00000000000
62525   01050510363  00000000000  00000000202  00000000235  00000000203  01050310367  00000000243  00000000202
62535   01050310371  00000000000  00000000202  01050310375  00000000235  00000000203  01050510377  00000000000
62545   00000000203  01050200001  00000000204  01050310403  00000000000  00000000203  01050310407  01050200001
62555   00000000204  01050510411  00000000000  00000000204  01050200003  00000000205  01050410415  00000000000
62565   00000000204  00000000222  01050410421  00000000000  00000000204  00000000223  01050310426  00000000000
625/5   00000000204  01050210432  00000000000  01050310434  01050200003  00000000205  01050310436  00000000250
62605   00000000205  01050410437  00000000231  00000000205  00000000230  01050310444  01050400005  00000000205
62615   01050410446  00000000251  00000000205  00000000246  01050510453  00000000240  00000000205  00000000247
62625   00000000206  01050410457  00000000240  00000000205  00000000247  01050510464  00000000240  00000000205
62635   00000000206  00000000270  01050510470  00000000000  00000000205  01050400005  00000000205  01050510475
62645   00000000000  00000000205  00000000243  00000000202  01050510502  00000000000  00000000205  00000000243
62655   01050300035  01050310507  00000000000  00000000205  01050510513  00000000250  00000000205  00000000247
62665   00000000303  01050510520  00000000250  00000000205  00000000247  00000000263  01050510525  00000000250
626/5   00000000205  00000000247  00000000265  01050510532  00000000250  00000000205  00000000247  00000000304
62705   01050510537  00000000250  00000000205  00000000247  00000000267  01050510544  00000000250  00000000205
62715   00000000247  00000000277  01050510551  00000000250  00000000205  00000000247  00000000300  01050510556
62725   00000000250  00000000205  00000000247  00000000273  01050510563  00000000250  00000000205  00000000247
62735   00000000274  01050510570  00000000250  00000000205  00000000247  00000000337  01050510575  00000000250
62745   00000000205  00000000247  00000000340  01050510602  00000000250  00000000205  00000000205  00000000271
62755   01050510607  00000000250  00000000205  00000000205  00000000272  01050510614  00000000250  00000000205
62765   00000000205  00000000301  01050510621  00000000250  00000000205  00000000205  00000000302  01050510626
```

```
62775   00000000250  00000000205  00000000206  00000000270  01050210633  00000000000  01050410635  00000000000
63005   00000000210  00000000232  01050310642  00000000000  00000000210  01050510646  00000000000  00000000211
63015   00000000234  00000000212  01050310652  00000000000  00000000211  01050310656  00000000234  00000000212
63025   01050510660  00000000000  00000000212  00000000233  00000000213  01050310664  00000000000  00000000212
63035   01050210670  00000000000  01050310672  00000000233  00000000213  01050310674  00000000244  00000000213
63045   01050410701  00000000251  00000000213  00000000246  01050510706  00000000000  00000000213  00000000243
63055   01050300035  01050510713  00000000000  00000000213  00000000243  00000000202  01050210720  00000000000
63065   01050310722  00000000000  00000000215  01050210726  00000000000  01050510730  00000000000  00000000217
63075   00000000241  00000000220  01050610733  00000000245  00000000217  00000000242  00000000220  00000000214
63105   01050410740  00000000251  00000000217  00000000275  01050310745  00000000000  00000000217  01050210751
63115   00000000000  01050610753  00000000245  00000000220  00000000242  00000000220  00000000214  01050410760
63125   00000000251  00000000220  00000000275  01050410765  00000000236  00000000220  00000000236  01050410771
63135   00000000242  00000000220  00000000214  01050410774  00000000245  00000000220  00000000214  01050311001
63145   00000000241  00000000220  01050211003  00000000000  01050411005  00000000200  00000000247  00000000270
63155   01050311012  00000000241  00000000206  01050211015  00000000000  01050411017  00000000240  00000000205
63165   00000000206  01050411023  00000000245  00000000205  00000000206  01050211030  00000000240  01050211033
63175   00000000250  01050211036  00000000000  01050211040  00000000236  01050211043  00000000254  01050211045
63205   00000000000  01050211050  00000000236  01050211051  00000000254  01050211053  00000000000  01050311056
63215   00000000000  00000000276  01050211063  00000000000  30000000000

          AUXILIARY PRODUCTION TABLE
65202   00000000000  00000000000  00000000215  00000000201  00000000205  00000000217  00000000240  30000000000
65212   30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000  30000000000
65222   30000000000  30000000000  30000000000  30000000000

          INTERPRETATION TABLE
65227   00010000001  00060000001  00070000004  00130000000  00070000741  00060000000  00060000001  00070000016
65237   00060000001  00070000060  00020000001  00140000000  00070000004  00020000001  00010000002  00060000001
65247   00070000004  00130000001  00070000741  00020000002  00010000003  00070000004  00020000003  00010000003
65257   00060000001  00070000004  00020000001  00060000000  00060000001  00070000032  00130000002  00070000741
65267   00060000000  00060000001  00070000037  00020000005  00010000004  00060000001  00070000045  00020000001
65277   00070000004  00020000002  00060000001  00070000004  00020000002  00030000000  00070000004  00130000003
65307   00070000741  00060000000  00060000001  00070000210  00060000000  00060000001  00070000704  00060000000
65317   00060000001  00070000103  00010000005  00060000001  00070000203  00060000001  00070000747  00020000001
65327   00030000215  00010000071  00060000001  00070000620  00060000000  00060000001  00070000121  00020000001
65337   00060000001  00070000060  00020000002  00130000023  00060000001  00070000060  00060000001  00070000103
65347   00020000001  00030000210  00010000006  00060000001  00070000536  00020000001  00030000201  00010000017
65357   00060000001  00070000125  00020000001  00030000201  00010000020  00060000001  00070000125  00020000001
65367   00030000210  00010000021  00060000001  00070000536  00060000000  00060000001  00070000210  00070000210
65377   00020000003  00010000007  00060000001  00070000060  00020000002  00030000202  00030000000  00070000260
65407   00020000002  00030000210  00030000000  00070000536  00020000002  00030000202  00030000000  00070000260
65417   00130000005  00070000733  00020000004  00030000201  00010000072  00060000001  00070000125  00020000002
65427   00030000205  00030000000  00010000010  00070000414  00020000002  00030000205  00030000000  00010000010
65437   00070000333  00020000003  00030000205  00030000000  00010000011  00070000715  00020000002  00030000206
65447   00030000000  00010000012  00060000001  00070000210  00020000002  00030000201  00030000000  00010000013
65457   00070000125  00130000006  00070000733  00020000002  00030000201  00010000014  00060000001  00070000125
65467   00020000002  00030000201  00010000015  00060000001  00070000125  00130000007  00070000733  00020000001
65477   00060000001  00070000060  00130000004  00070000733  00060000001  00070000103  00060000001  00070000141
65507   00060000001  00070000210  00060000000  00060000001  00070000210  00060000000  00060000001  00070000210
65517   00060000000  00060000001  00070000210  00060000001  00070000173  00060000001  00070000173  00020000001
65527   00030000202  00010000016  00060000001  00070000260  00020000001  00030000202  00010000017  00060000001
65537   00070000260  00020000001  00030000202  00010000020  00060000001  00070000260  00060000000  00060000001
65547   00070000210  00020000001  00030000205  00010000022  00060000001  00070000414  00020000001  00030000201
65557   00010000023  00060000001  00070000125  00020000001  00030000202  00010000024  00060000001  00070000260
65567   00060000001  00070000210  00020000001  00030000205  00010000061  00060000001  00070000333  00020000001
```

```
65577   00030000202 00010000026 00060000001 00070000260 00020000001 00030000202 00010000102 00060000001
65607   00070000260 00130000022 00070000733 00020000003 00030000000 00010000025 00070000273 00060000001
65617   00070000103 00020000032 00030000203 00030000000 00070000273 00060000001 00070000210 00020000003
65627   00030000000 00010000027 00070000306 00020000002 00030000204 00030000000 00070000306 00060000001
65637   00070000210 00020000003 00030000000 00010000030 00070000333 00020000003 00030000205 00030000000
65647   00070000333 00020000003 00030000205 00030000000 00010000031 00070000333 00020000002 00030000205
65657   00030000000 00070000333 00130000010 00070000733 00060000001 00070000210 00070000414 00020000003
65667   00030000201 00010000032 00060000001 00070000125 00060000001 00070000210 00020000003 00030000202
65677   00010000033 00060000001 00070000260 00020000003 00030000001 00030000000 00070000715 00020000003
65707   00030000001 00010000033 00060000001 00070000210 00020000002 00010000034 00060000001 00070000103
65717   00020000004 00030000210 00030000000 00010000035 00070000536 00020000004 00030000215 00030000000
65727   00010000036 00070000620 00020000004 00030000215 00030000000 00010000037 00070000620 00020000002
65737   00030000210 00030000001 00070000536 00020000004 00030000001 00010000040 00060000001 00070000333
65747   00020000004 00030000215 00010000041 00060000001 00070000620 00020000004 00030000215 00010000042
65757   00060000001 00070000620 00020000004 00030000202 00010000043 00060000001 00070000260 00020000004
65767   00030000215 00010000044 00060000001 00070000620 00020000004 00030000215 00010000045 00060000001
65777   00070000620 00020000004 00030000215 00010000046 00060000001 00070000620 00020000004 00030000001
66007   00010000047 00060000001 00070000333 00020000004 00030000215 00010000050 00060000001 00070000620
66017   00020000004 00030000210 00010000100 00060000001 00070000536 00020000004 00030000215 00010000101
66027   00060000001 00070000620 00020000004 00030000215 00010000051 00060000001 00070000620 00020000004
66037   00030000215 00010000052 00060000001 00070000620 00020000004 00030000215 00010000066 00060000001
66047   00070000620 00020000004 00030000210 00010000070 00060000001 00070000536 00020000004 00030000215
66057   00010000053 00060000001 00070000620 00130000011 00070000733 00020000003 00030000211 00030000000
66067   00010000054 00070000545 00020000002 00030000211 00030000000 00070000545 00020000003 00030000000
66077   00010000055 00070000555 00020000002 00030000212 00030000000 00070000555 00060000001 00070000103
66107   00020000003 00030000000 00010000056 00070000572 00020000002 00030000213 00030000000 00070000572
66117   00130000012 00070000733 00060000001 00070000103 00020000002 00030000214 00010000057 00060000001
66127   00070000060 00020000003 00030000210 00010000060 00060000001 00070000536 00020000004 00030000215
66137   00030000000 00010000037 00070000620 00020000004 00030000215 00030000000 00010000062 00070000620
66147   00130000013 00070000733 00020000002 00030000217 00030000000 00070000625 00130000014 00070000733
66157   00020000003 00030000000 00070000651 00020000005 00030000001 00010000065 00060000001 00070000625
66167   00020000003 00030000001 00010000064 00060000001 00070000625 00020000002 00030000220 00030000000
66177   00070000651 00130000015 00070000733 00020000005 00030000217 00010000065 00060000001 00070000625
66207   00020000003 00030000217 00010000064 00060000001 00070000625 00020000003 00010000073 00060000001
66217   00070000004 00010000067 00060000001 00070000060 00020000003 00030000217 00010000063 00060000001
66227   00070000625 00060000001 00070000060 00130000017 00070000733 00020000002 00030000206 00010000077
66237   00060000001 00070000710 00020000001 00060000001 00070000103 00130000070 00070000733 00020000001
66247   00010000074 00060000001 00070000715 00020000003 00030000201 00010000075 00060000001 00070000725
66257   00020000001 00060000001 00070000725 00020000001 00060000001 00070000125 00130000021 00070000733
66267   00020000001 00060000001 00070000004 00140000000 00070000733 00020000001 00060000001 00070000733
66277   00070000004 00140000000 00070000733 00020000001 00060000001 00070000741 00020000002 00030000215
66307   00010000076 00060000001 00070000620 00130000024 00070000733
        TAPE 8    4
             RECORD TYPE                   NUMBER OF RECORDS   STARTING RECORD

        SYMBOL TABLE                               1                  8
        HIERARCHY TABLE                            2                  9
        PRODUCTION TABLE                           1                 13
        METACHARACTER LISTS                        2                 14

      TIME USEDI  00105102     PAGES USEDI    11            19108118
```

Appendix F

This appendix consists of three sample programs written in the small language and translated by the compiler built from Appendices B and C. None of the programs are meant to do useful computations, but rather to illustrate the functioning of the compiler.

Example 1 is a correct program involving fairly complicated uses of conditional and arithmetic statements. Example 2 is somewhat simpler, but has been run with several trace options on. Example 3 contains an example of a semantic error, as well as some fairly complex code. The interested reader can get a good idea of the type of code produced by the system from these examples. However, the lack of really involved structures (procedures, etc.) in the small language may yield an unrealistically optimistic picture of the sytem's performance.

```
****************************************************************************/*/**************************************************************************

OPERATOR-040 14 MAY 64  19:10:11  MAGIC  PAGES:  50  TIME:   1                          CC35.013     J. FELDMAN
                                                                                                   COMPUTER CENTER

                                                          00:00:04(1)

CO                   EXAMPLE 1
SN         DUMP 1
    BEGIN REAL X,Y,ZEBRA; BOOLEAN P,Q; LABEL L1,L2;
     L1: Y← X*Y-ZEBRA↑(Y/2) ;
       IF IF P THEN Q ELSE X=3 THEN BEGIN X← X-1; GOTO L1 END
                   ELSE GOTO L2;
       X← X+1; GOTO L1;
    L2: Q← TRUE
            END
20000     0 CLA 2 40000,00     0 MPY 2 40002,00     0 STD 0 72400,77     0 CLA 2 40002,00     0 DIV 0 00002,00
20005     0 STD 0 72652,00     0 CLA 2 40004,00     0 STD 0 72650,00     0 TRM 0 10253,00(3)  0 SUN 2 72400,77
20012     0 STD 0 40002,00     0 CLA 2 40000,00     0 FUO 0 00003,00     0 OCA 0 00001,00     0 CCL 2 14376,00
20017     0 IOZ 2 40006,00(5)  0 TRA 0 20024,00     0 CAL 2 40007,00     0 STL 0 72400,77     0 TRA 0 20025,00
20024     0 STL 0 72400,77     0 ICZ 2 72400,77     0 TRA 0 20030,00     0 TRA 0 20035,00     0 CLA 2 40000,00
20031     0 SUB 0 00001,00     0 STD 0 40000,00     0 TRA 0 20000,00     0 TRA 0 20036,00     0 TRA 0 20042,00
20036     0 CLA 2 40000,00     0 ADD 0 00001,00(4)  0 STD 0 40000,00     0 TRA 0 20000,00     0 CAL 2 14377,00
20043     0 STL 0 40007,00     0 TRM 0 05300,00


        TIME USED:  00:00:07(2)  PAGES USED:    1              19:10:17
```

1. The compiler took four seconds to read in the tables of the small language.
2. Three seconds were used to compile and dump the program.
3. ↑ is executed by a library subroutine.
4. Location 5300 is the monitor HALT routine.
5. Temporaries start at 72400; the index register allows recursive use of temporaries.

```
*******************************************************************************************************************************
OPERATOR-040 14 MAY 64  19:18:37  MAGIC  PAGES:  20  TIME:   3                               CC35.013   J. FELDMAN
                                                                                                          COMPUTER CENTER

                                                              00:00:04

CO                      EXAMPLE 2
SN   ①   CODE 1
SN   ②   EXEC 1
SN        DUMP
     BEGIN REAL X,Y,ZEBRA; BOOLEAN P,Q; LABEL L1,L2;
00061    00000000001
63334    00000000252  00000000000  00000000000  00000000000  00000000000  00000000252  00000000213  00000000213
00061    00000000004
63334    00000000234  00000000262  00000000246  00000000000  00000000000  00000000234  00000000262  00000000246
00061    00000000004
63334    00000000234  00000000263  00000000246  00000000000  00000000000  00000000234  00000000263  00000000246
00061    00000000004
63334    00000000235  00000000264  00000000246  00000000000  00000000000  00000000235  00000000264  00000000246
00061    00000000005
63334    00000000234  00000000265  00000000250  00000000000  00000000000  00000000234  00000000265  00000000250
00061    00000000005
63334    00000000235  00000000266  00000000250  00000000000  00000000000  00000000235  00000000266  00000000250
00061    00000000036
63334    00000000234  00000000267  00000000251  00000000000  00000000000  00000000234  00000000267  00000000251
00061    00000000036
63334    00000000235  00000000270  00000000251  00000000000  00000000000  00000000235  00000000270  00000000251
      L1: IF (X*Y)/(X+Y) = ZEBRA THEN
00061    00000000002
63334    00000000267  00000000246  00000000252  00000000000  00000000000  00000000267  00000000235  00000000252
00061    00000000032
63334    00000000236  00000000267  00000000252  00000000000  00000000000  00000000235  00000000252  00000000213
00061    00000000011
63334    00000000262  00000000267  00000000252  00000000000  00000000000  00000000262  00000000242  00000000255
00061    00000000011
63334    00000000263  01030040000  00000000252  00000000000  00000000000  00000000263  00000000216  01030040000
00061    00000000012
63334    00000000245  01030040002  00000000216  01030040000  00000000000  00000000245  01030040000  00000000242
20000    04050040000
20001    04770040002
00061    00000000017
63334    00000000245  00030400000  00000000242  01030040000  00000000000  00000000242  00000000255  00000000235
00061    00000000011
63334    00000000262  00030400000  00000000242  01030040000  00000000000  00000000262  00000000242  00000000217
00061    00000000011
63334    00000000263  01030040000  00000000242  01030040000  00000000000  00000000263  00000000214  01030040000
00061    00000000014
63334    00000000245  01030040002  00000000214  01030040000  00000000000  00000000245  01030040000  00000000242
20002    01537772400
20003    04050040000
20004    04450040002
00061    00000000017
63334    00000000245  00030400000  00000000242  01030040000  00000000000  00000000242  01032072400  00030400000
```

```
00061    00000000013
63334    00000000220   00030400000   01032072400   00030400000   00000000000   00000000220   00030400000   00000000255
20005    00570040002
00061    00000000011
63334    00000000264   00030400000   01032072400   00030400000   00000000000   00000000264   00000000220   00030400000
00061    00000000021
63334    00000000256   01030040004   00000000220   00030400000   00000000000   00000000256   00030400000   00000000255
20005    05610040004
.20007   00000000001
20010    04150014376
20010    04350014376
00061    00000000025
63334    00000000256   00000400000   00000000255   00030400000   00000000000   00000000255   00000000235   00000000252
00061    00000000003
63334    00000400000   00000400000   00000000255   00030400000   00000000000   00000400000   00000000235   00000000252
20007    00170000000
20010    00170000000
  .      BEGIN X← -X+ZEBRA; GOTO L2 END ELSE P← FALSE;
00061    00000000002
63334    00000000262   00000000252   00000000255   00030400000   00000000000   00000000262   00000000235   00000000252
00061    00000000011
63334    00000000262   00000000252   00000000255   00030400000   00000000000   00000000262   00000000215   00000000237
00061    00000000016
63334    00000000214   01030040000   00000000215   00030400000   00000000000   00000000214   00000000215   00000000237
00061    00000000011
63334    00000000264   01030040000   00000000215   00030400000   00000000000   00000000264   00000000214   01034040000
00061   3 0000000014                             4
63334    00000000235   01030040004   00000000214   01034040000   00000000000   00000000235   01034040000   00000000237
20011    04250040000
20012    04450040004
00061    00000000020
63334    00000000235   00030400000   00000000237   00000000262   00000000000   00000000235   00000000262   00000000235
20013    01530040000
00061    00000000031
63334    00000000270   00000000254   00000000237   00000000262   00000000000   00000000254   00000000235   00000000252
20014    00170000000
00061    00000000035
63334    00000000253   00000000254   00000000235   00000000252   00000000000   00000000252   00000400000   00000000235
00061    00000000006
63334    00000000257   00000000252   00000400000   00000000252   00000000000   00000000257   00000000252   00000400000
20015    00170000000
00061    00000000030
63334    00000000235   01000214376   00000000237   00000000265   00000000000   00000000235   00000000265   00000000257
20016    04150014376
20017    01730040006
00061    00000000033
63334    00000000235   00000000265   00000000257   00000000252   00000400000   00000000235   00000000265   00000000235
     L2: IF P THEN X← Y↑ZEBRA; Q← X<Y
00061    00000000032
63334    00000000236   00000000270   00000000257   00000000252   00000400000   00000000235   00000000252   00000000213
00061    00000000024
63334    00000000256   00000000265   00000000257   00000000252   00000400000   00000000256   00000000265   00000000255
00061    00000000025
63334    00000000256   01000040006   00000000255   00000000252   00000400000   00000000255   00000000235   00000000252
00061    00000000003
```

```
63334    01000040006  01000040006  00000000255  00000000252  00000400000  01000040006  00000000235  00000000252
20020    04310040006
20021    00170000000
20022    00170000000
00061    00000000010
63334    00000000231  00000000263  00000000255  00000000252  00000400000  00000000231  00000000263  00000000237
00061    00000000011
63334    00000000264  01030040002  00000000255  00000000252  00000400000  00000000264  00000000231  01030040002
00061    00000000034
63334    00000000235  01030040004  00000000231  01030040002  00000400000  00000000235  01030040002  00000000237
20023    04050040004
20024    01530072652
20025    04050040002
20026    01530072650
20027    01770010253
00061    00000000020
63334    00000000235  00030400000  00000000237  00000000262  00000400000  00000000235  00000000262  01000040006
20030    01530040000
00061    00000000007
63334    00000000235  00000000262  01000040006  00000000262  00000400000  00000000235  01000040006  00000000235
00061    00000000010
63334    00000000224  00000000262  01000040006  00000000262  00000400000  00000000224  00000000262  00000000237
00061    00000000011
63334    00000000263  00000000262  01000040006  00000000262  00000400000  00000000263  00000000224  01030040000
        END
00061    00000000022
63334    00000000253  01030040002  00000000224  01030040000  00000400000  00000000253  01030040000  00000000237
20031    04050040000
20032    05210040002
20033    00000000001
20034    04150014376
00061    00000000027
63334    00000000253  00000400000  00000000237  00000000266  00000400000  00000000253  00000000266  00000000235
20035    01730040007
00061    00000000035
63334    00000000253  00000000266  00000000235  00000000252  00000400000  00000000252  00000000213  00000000213
00061    00000000037
63334    00000000252  00000000213  00000000235  00000000252  00000400000  00000000213  00000000213  00000000213
20035    01770005300
20000     0 CLA 2 40000,00     0 MPY 2 40002,00     0 STD 0 72400,77     0 CLA 2 40000,00     0 ADD 2 40002,00
20005     0 RDV 0 40002,00     0 FUO 2 40004,00     0 TRA 0 20011,00     0 TRA 0 20016,00     0 CLS 2 40000,00
20012     0 ADD 2 40004,00     0 STD 0 40000,00     0 TRA 0 20020,00     0 TRA 0 20020,00     0 CAL 2 14376,00
20017     0 STL 0 40006,00     0 ICZ 2 40006,00     0 THA 0 20023,00     0 TRA 0 20031,00     0 CLA 2 40004,00
20024     0 STD 0 72652,00     0 CLA 2 40002,00     0 STD 0 72650,00     0 TRM 0 10253,00     0 STD 0 40000,00
20031     0 CLA 2 40000,00     0 FLO 2 40002,00     0 OCA 0 00001,00     0 CAL 2 14376,00     0 STL 0 40007,00
20036     0 TRM 0 05300,00


         TIME USED!  00:00!14    PAGES USED!    3             19!18!50
```

1. This causes the code to be printed as it is compiled.
2. Causes the routine number and LEFT1-LEFT5 and RIGHT1-RIGHT3 to be printed.
3. EXEC 12 ↓ is called to add -X and ZEBRA, it knows to subract X because of ④
4. The negation is bit set in LEFT4.

```
################################################################################################# 

OPE(AIOR-040 14 MAY 64  19:11:05  MAGIC  PAGES:  50  TIME:   1                        CC33 [illegible]


                                                             00:00:04

CO                        EXAMPLE 3
SN         DUMP
                        BEGIN
        BEGIN REAL X,Y, ZEDD; BOOLEAN P,Q,ZEDE;
        ZEDE ← IF X/Y+ZEDD-X = X THEN P ELSE Q;
            X ← X*X + X*X END
                         ;
       BEGIN REAL X, Y, Z; BOOLEAN P,Q;
           X ← Y + X*X*Z; (3)
        X ←  I*I; Y ← 1.5; Z ← X/3;
(1)FAULT    1
FAULT       1
       P ← TRUE;  Q ← FALSE      ;
        P ← Q END
           END
20000      0 CLA 2 40000,00    0 DIV 2 40002,00    0 ADD 2 40004,00    0 SUB 2 40030,00    0 ADD 2 4000[illegible]
20005      0 TRA 0 20011,00    0 CAL 2 40006,00    0 STL 0 72400,77    0 TRA 0 20013,00    0 CAL 2 4000[illegible]
20012      0 STL 0 72400,77    0 CAL 2 72400,77    0 STL 0 40010,00    0 CLA 2 40010,00    0 MPY 2 4000[illegible]
20017      0 STD 0 72401,77    0 CLA 2 40000,00    0 MPY 2 40000,00    0 ADD 2 72401,77    0 STO 0 4000[illegible]
20024      0 CLA 2 40011,00    0 MPY 2 40011,00    0 MPY 2 40015,00    0 ADD 2 40013,00    0 STO 0 4001[illegible]
20031   (2)0 CAL 0 00271,00    0 STD 0 72652,00 (2)0 CAL 0 00271,00    0 STD 0 72650,00    0 TR[illegible] 0 [illegible]
20036      0 STD 0 40011,00    0 CLA 2 14401,00    0 STD 0 40013,00    0 CLA 2 40011,00    0 D[illegible] 0 000[illegible]
20043      0 STD 0 40015,00    0 CAL 2 14377,00(4) 0 STL 0 40017,00    0 CAL 2 14376,00(4) 0 ST[illegible] 0 400[illegible]
20050      0 CAL 0 40020,00    0 STL 0 40017,00    0 TRM 0 05300,00


        TIME USED:  00:00:08    PAGES USED:    1               19:11:12
```

1. The semantic error message FAULT 1 is printed twice because 'I' was not declared.

2. Since OK was not set FALSE, translation continues using the internal name of 'I' as its [illegible].

3. The floating point constant '1.5' is put in a cell in the constant region.

4. TRUE and FALSE are also absolute constants.